Impact of Residential Photovoltaic Generation and Electric Vehicles on Distribution Transformers

Progress Report #1
April 08, 2013

In this document:

• Evaluation of power system modeling software
• Description of computer model of Mueller Community
• Case study on the impact of PVs and EVs to distribution transformers
• Conclusions and observations

This report is part of a series of reports produced by the Center for Electromechanics of The University of Texas at Austin under sponsorship by Pecan Street, Inc. This document is meant for view in color.

Center for Electromechanics
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# Table of Contents

Executive Summary.......................................................................................................................... vi

1 Introduction...................................................................................................................................... 1

2 The Mueller Community.................................................................................................................. 3
   2.1 Overview..................................................................................................................................... 3
   2.2 Electric Service.......................................................................................................................... 4

3 Software Evaluation....................................................................................................................... 17
   3.1 Simulation Type......................................................................................................................... 17
   3.2 Software Evaluation................................................................................................................... 20

4 Computer Model............................................................................................................................. 24

5 Case Study...................................................................................................................................... 28
   5.1 Residential Load......................................................................................................................... 28
   5.2 PV Generation............................................................................................................................ 31
   5.3 Electric Vehicles......................................................................................................................... 33
   5.4 Transformer Impact.................................................................................................................... 34
      5.4.1 Real Power........................................................................................................................... 35
      5.4.2 Total Percent Utilization....................................................................................................... 36
      5.4.3 Transformer Voltage Profiles.............................................................................................. 37
      5.4.4 Transformer Utilization: Before and After......................................................................... 39
      5.4.5 Change in Transformer Utilization...................................................................................... 40
   5.5 Lateral Analysis........................................................................................................................... 42
      5.5.1 Power Breakdown............................................................................................................... 42
      5.5.2 Power Demand..................................................................................................................... 43
      5.5.3 Lateral Current..................................................................................................................... 44
   5.6 Distribution Losses...................................................................................................................... 46

6 Conclusions................................................................................................................................... 48

References.......................................................................................................................................... 51
List of Figures

Fig. 1.1 Project time line showing work period of this report (amber color) and milestones showing the release of YouTube videos .................................................................1

Fig. 2.1. *Left:* Mueller homes equipped with rooftop PVs (6 kW each). *Right:* Second (research) meter in a dual socket configuration. (*Image Source:* Pecan Street) .........................4

Fig. 2.2 Aerial view of Mueller community. The two substations serving this community are in the surrounding area (*Image Source:* Google Earth). ......................................................5

Fig. 2.3 One-line diagram of Mueller Community including 735 homes, 94 transformers, 176 PVs, and 100 EVs (Austin, Texas).................................................................................7

Fig. 2.4 Counts and percentages of transformers, homes, PVs, and EVs in each phase........12

Fig. 2.5 Asset counts by phase (top) and circuit (bottom) ..................................................13

Fig. 2.6 PV generation in each phase (kW) at Mueller ......................................................14

Fig. 2.7 Transformer count and approximate cost [7] ..........................................................16

Fig. 3.1 Comparison between phasor and instantaneous (continuous) values .................19

Fig. 4.1 Computer of the Mueller community built in MATLAB/Simulink.........................24

Fig. 4.2 Mueller community computer model. View of phase *a*, circuit 1 ......................25

Fig. 4.3 Mueller community computer model. Close-up view of phase *b*, circuit 2 ..........26

Fig. 4.4 Transformer load model accepting the recorded data provided by Pecan Street......26

Fig. 4.5: Chevy Volt charging profiles (1-min. interval) collected by Pecan Street..........27

Fig. 5.1: Residential demand for 735 homes in a 24-hour period (data interval: 1 minute). 29

Fig. 5.2: Residential energy usage for each home (24-hour period). *Left:* average energy usage for each home and across all homes (23 kWh). *Right:* energy consumption distribution showing that most homes consume 15 kWh per day. ..................................................30

Fig. 5.3: Solar generation for all 178 PVs in a 24-hour period. Data interval: 1 min........31

Fig. 5.4: Charging profiles for all 100 electric vehicles in a 24-hour period. Data interval: 1 min

....................................................................................................................................33

Fig. 5.5: Real power through all distribution transformers .................................................36

Fig. 5.6: Percent-utilization of all distribution transformers ..............................................37

Fig. 5.7: Transformer oltage profiles (secondary side) ......................................................38
Fig. 5.8: Transformer utilization before (left) and after (right) the penetration of PVs and EVs. Circled area exemplifies change due to PVs; the square is an exempl of impact due to EVs.

Fig. 5.9: Change in transformer utilization. *Left*: color indicates %-change; “-“ sign indicates less utilization than before; “+” sign indicates more utilization than before. *Right*: 

Fig. 5.10: Breakdown of all aggregate power profiles.

Fig. 5.11: Total power demand as seen from the main lateral service entrance (*Left*: before PVs and EVs; *Right* after PVs and EVs).

Fig. 5.12: Per-phase current entering the lateral service entrance (*Left*: before PVs and EVs; *Right* after PVs and EVs).

Fig. 5.13: Cable, transformer, and total distribution losses in watts and dollars. *Left*: before PVs and EVs; *Right* after PVs and EVs.
List of Tables

Table 2-1 Distribution transformer types .....................................................................................7
Table 2-2 Distribution transformer and their asset counts ............................................................8
Table 2-3 Asset / load counts .................................................................................................... 10
Table 2-4 Asset / load ratings .................................................................................................... 11
Table 2-5 Photos of each transformer size at Mueller (photos taken by CEM) ........................... 15
Table 2-6 Impedance information for each transformer type (courtesy of Austin Energy) .......... 15
Table 3-1 Comparison between load flow and transient simulation ............................................ 18
Table 3-2 Software considered for the simulation......................................................................21
Executive Summary

Pecan Street Inc., with the cooperation of the residents of the Mueller development in Austin, is generating an extensive database of electricity usage with good time resolution and spatial resolution to the individual residence. With funding from Pecan Street, Inc. (Pecan Street) and the cooperation of Austin Energy, one of Pecan Street's utility partners, researchers from the University of Texas at Austin have developed a model of the electrical distribution system. This model uses the available data to assess the state of the distribution system under existing conditions. With the confidence developed from this effort, predictions of operation under other scenarios can be performed. This capability is particularly important in areas like the Mueller development, in which growth and the addition of new technologies, like rooftop photovoltaic systems and plug-in vehicles, are dramatically changing the demands on the electrical distribution system.

Key activities in this investigation included:

- the development of an up-to-date one-line diagram and associate geospatial information describing the distribution system in the Mueller neighborhood

- the development of a computer model that uses the data generated by Pecan Street and the topology of the distribution system to assess the state of the entire distribution system under the conditions measured and to use the measured data to predict system implications of component or operational changes

- the exercise of creating a model to simulate situations of interest.

Observations from this investigation include

- With the 735 homes modeled, using the measured data, the average home, without either a photovoltaic system or a plug-in vehicle, consumed about 24 kWh per day. Variations by individual homes from the average were significant in the temporal variations of electricity usage

- 178 photovoltaic systems were installed and added to the model. While there is a significant similarity, important variations do occur in this distributed system due to differences in orientation, the passage of clouds, and other features.

- The potential impact of plug-in vehicles was assessed by combining the measured electricity demand while charging a Chevrolet Volt and randomly inserting 100 of these vehicles with their chargers across the 735 houses. Charge start times were randomized between 4:00 p.m. and 8:00 p.m. In addition, the state of charge was also randomized. This set of assumptions led to insignificant effects on either the distribution transformers or the power requirements on the lateral feeder to the neighborhood. It is noted that the work is based on the current model of Chevy Volt, which charges at a lower kW than is now available in other electric vehicles.
The average transformer load is about 7 kW and the peak is about 40 kW. Some transformers act as step-up transformers, powering the local distribution system when solar irradiance is high.

Most of the time, the transformers operate at 10% to 30% of their capacity. For some short periods, they can operate at 90% of capacity.

On high solar irradiance days, the power factor for the neighborhood was estimated at 0.6, which means the utility is providing nearly as much reactive power as real power. This estimate is an aggregate result based on the estimated power factor of each home, which varies between 0.7 lagging and 0.7 leading. The power factor is low due to the fact that the solar systems only provide real power.

Even with photovoltaic systems and plug-in vehicles, the impact of load or source variations on transformer secondary voltage appears to be negligible.

Transformer utilization with the photovoltaic systems and plug-in vehicles is a more complex story. The vehicles merely increase utilization as more vehicles are added. Due to the randomness of human behavior, however, the change in utilization is complex to predict. The photovoltaic systems add even more complexity because to the extent they are producing less power than required on the consumer side of the transformer, they reduce transformer utilization. If more power is produced than needed, the transformers serve as a step-up transformer, providing power to the circuit and increasing transformer utilization.

The addition of the photovoltaic systems and the plug-in vehicles did not increase the distribution system losses in this case to any significant extent. This is likely a particular observation to this installation rather than a general result.

This unique combination of a system model and data has been used to provide unprecedented insight into the behavior of every transformer and every cable in the system. There is still significant work that can be done with this tool to get additional and useful information. Potential future studies include assessment of the amount of photovoltaic systems and electric vehicles that can cause problems for the distribution systems, sizing for community storage to minimize potential problems, and modifications to the system to permit intentional islanding and reliable power during outages.
1 Introduction

The focus of this report is on the analysis of the impact of residential photovoltaic arrays (PVs) and electric vehicles (EVs) on the local power utility’s distribution transformers. The work was performed by the Center for Electromechanics (CEM) of the University of Texas at Austin (UT) between June 2011 and June 2012.

Fig. 1.1 shows the overall timeline for this project, where the amber-color time span shows the work period covered by this report. The annotated milestone markers show dates and topics for supplementary videos produced by the authors available on YouTube for public view. These videos are meant to be informative, to share the author’s progress, acknowledge Pecan Street as the rightful data provider, and share interim results with UT students, professors, Pecan Street’s industry advisor consortium, and the general public. (Videos available on CEM’s YouTube channel: http://www.youtube.com/user/utcem.)

Fig. 1.1 Project time line showing work period of this report (amber color) and milestones showing the release of YouTube videos

Pecan Street is a non-profit organization headquartered at The University of Texas at Austin (UT). Pecan Street staff members and researchers at UT carry out customer research trials, original research, and commercialization efforts addressing consumer energy use in light of an existing Smart Grid in Austin, Texas.

This organization is a major source of original customer energy use and behavioral research data and operates data-intensive field trials open to researchers and member companies. Pecan Street instruments homes and commercial buildings in its research trials with systems that record electricity use from the whole building and individual circuits at intervals ranging from one minute to one second.

Pecan Street’s core research assets include research data on consumer electricity and natural gas use. The consumer smart grid field trials are accessible to companies interested in proprietary applications, and can access anonymous data on the utility- and customer-side of the utility meter. Pecan Street also has a commercialization lab for product development and performance
testing to commercialize early stage technologies from companies carrying out product testing and development; particularly residential and small commercial applications involving smart grid, distributed generation, consumer natural gas, and building management and consumer relations.

This report presents an analysis of some of the data collected by Pecan Street. This work combined available data with a custom-developed model of the neighborhood power system. This combination is the strength of the investigation. Data, without a model, is useful only for aggregate and approximate retrospective studies. A model, without supporting data, is useful, but always suspect because unrealistic assumptions may have been made. The combination provides a tool to realistically assess and predict system states. System states are of interest to utilities concerned about the impact of emerging technologies on their distribution assets.

This report summarizes research into the extent to which high concentrations of PVs and EVs affect the distribution system. The authors use 2-D and 3-D contour visualization techniques to summarize results for Pecan Street, its consortium members, the local power utility, and general readership.

This report is organized into the following chapters:

- Chapter 2: introduces the Mueller Community and highlights its electrical infrastructure
- Chapter 3: summarizes the evaluation of select power system modeling tools
- Chapter 4: introduces the computer model developed by the authors
- Chapter 5: presents the results and analysis of this work
- Chapter 6: provides concluding observations
2 The Mueller Community

This chapter presents an overview of the Mueller community and a basic description of its electric service. Sufficient details are given in this section for readers to understand the electrical infrastructure at Mueller, and to develop a computer model as exemplified in the next chapter. Some details are omitted in recognition of privacy concerns.

2.1 Overview

The Mueller development is a 711-acre mixed-use development in which every new building is green built (as certified through LEED or Austin Energy’s nationally recognized Green Building program). The development is an urban in-fill redevelopment, built on the site of Austin’s former municipal airport (closed in 1999). It is a prototypical development model, similar to hundreds like it across the United States.

The development, which is less than 50% complete, is being executed as a public-private project between the City of Austin and Catellus Austin, LLC. The development includes 25% affordable housing, the world’s first LEED Platinum hospital, a reclaimed water irrigation system, and native landscaping selected in part for the selected plants’ low water consumption and carbon sequestration capacity.

The project is collecting data from this demonstration project to analyze the results against control groups and distribution feeder systems in other locations in the City of Austin. This project is also quantifying how integration of these technologies impact customer electric bills, energy usage, utility finances, environmental outcomes and electric system performance. UT researchers are working with Austin Energy and project participants to collect, measure, quantify, and analyze project metrics relating to electrical system architecture and performance, green building impacts and energy usage impacts from water system smart grid integration.

This modern mixed-use development, which already features a comprehensive approach to the advanced efficiency technologies and environmental strategies of today, provides an advanced platform on which to test the impacts of a concentrated deployment of the technologies we expect to make up tomorrow’s smart grid, while also demonstrating a commitment to environmental sustainability and social equity.

Mueller was designed to exemplify Austin’s interpretation of smart growth: a vibrant mix of uses positioned within a dense, walkable design to encourage non-vehicular transportation. At full build out, the project will include more than 4,900 single-family and multi-family dwelling units with an average density of approximately 26 units/acre; and more than 3 million square feet of commercial and institutional space anchored by the Dell Children’s Medical Center of Central Texas, the Austin Film Studio and at least 790,000 square feet of retail space. At completion, Mueller will be home to some 10,000 permanent jobs. The project also includes a site for an elementary school, some 140 acres of parks and open space, and a requirement that a quarter of all new residential units are affordable to households earning less than the median family income.

Nearly 200 homes at Mueller are instrumented with secondary (second energy meter) and tertiary (meters inside the homes) metering to report electrical data in one minute and one second intervals, and gas data in 15 second intervals. More than 50 homes report 15 second interval
water use. The research trials include what is likely the nation’s highest residential concentration of electric vehicles with Level-2 charging. Many homes are equipped with rooftop solar PV panels, of which 40 % is west-facing (the nation’s highest residential concentration of west-facing, load-aligned PV generation). A picture of the Mueller community (residential portion) showing the high concentration of residential PVs is shown in Fig. 2.1.

![Image 1](image1.jpg)

**Fig. 2.1.** Left: Mueller homes equipped with rooftop PVs (6 kW each). Right: Second (research) meter in a dual socket configuration.  *(Image Source: Pecan Street)*

Pecan Street team has deployed a second (research) meter in a dual socket configuration (right) as well as wireless data collection systems inside each home (at the circuit level). The meter outside each home (in addition to the utility meter) captures data, in 1 minute intervals, for the whole home (including PV generation), and reports this data, via an intermediary, who helps assure data anonymity, to Pecan Street’s consumer energy data center at UT’s Texas Advanced Computing Center. The wireless meters inside the homes capture data in 15 second intervals across six radial circuits (e.g., air condition circuit, EV charging circuit, among other). The data used in the research in this report was downloaded from the Texas Advanced Computing Center.

### 2.2 Electric Service

Two surrounding substations provide electric service to the Mueller community. Substation 1 serves 91 distribution transformers while substation 2 serves the remainder 3.

A satellite view¹ of the Mueller community is shown in Fig. 2.2. The community, at the center of the figure, has its substations located in the surrounding areas. These substations are owned by the local power utility (Austin Energy) and serve the residential and commercial electrical loads in the community.

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¹ Screenshot taken using *Google Earth*
Fig. 2.2 Aerial view of Mueller community. The two substations serving this community are in the surrounding area (Image Source: Google Earth).

A one-line diagram of the Mueller community is shown in Fig. 2.3. Substation 1 is shown along the top of the figure with its two transformers rated at 30 MVA each. These transformers step down sub-transmission voltage (69 kV) to distribution-level voltage (12.47 kV) [1]. Each transformer serves three feeders at 12.47Y/7.2 kV. Each feeder, in turn, serves other urban communities or commercial areas via service laterals. Following feeder 1 downward from substation 1, along various locations along the feeder are capacitor banks. (This is true of other feeders as well.) These capacitor banks are controlled by diurnal light and are meant to improve service quality in the surrounding areas. For example, these capacitors provide power factor correction, reduce feeder voltage drops, and provide voltage and reactive power support. (Resonance issues, if any, of capacitor banks and PVs are not investigated in this report.) Transformer 2 (T2) at substation 1 is in service, but appears disconnected in the one-line diagram. This is because the focus of this work is the electric service to Mueller, not to the neighboring areas serviced by T2 and substation 2. Although understanding of the behavior of neighbor areas (as well as the impact of Mueller on them) is important, it is not studied because their concentrations of PVs and EVs are not as high as they are at Mueller.
Shown from left-to-right in Fig. 2.3 is the lateral service entrance to the Mueller community. When initially analyzed, one lateral served the community. Subsequently, an additional feeder from substation 2 was installed to support phase \( c \) (shown on the bottom right of Fig. 2.3). While this is currently true and was accounted for in the computer model (presented later), most of the electric service provided from substation 1 will likely be moved to substation 2. This change does not affect the approach or the conclusions of the analysis. It does, however, provide a new configuration that can be modeled.

The lateral service entrance shows values of 1.5 MVA at 12.47 kV. The MVA value is an estimate of the total load looking into the community from the lateral service entrance. This estimate suggests that Mueller constitutes roughly \( 100 \times 1.5/30 = 5\% \) of substation 1’s transformer (T1) capacity, which is small in relation to T1’s capacity. It is also unlikely the T1 operates at its rated capacity of 30 MVA. The true impact of Mueller to the substation, therefore, remains uncertain, but small. However, the lessons learned from the Mueller community likely apply to neighbor communities as PVs and EVs continues to proliferate [2].

The conductors emanating from feeder in Fig. 2.3 (and lateral) are shown in red, blue, and green. These colors represent electrical phases \( a, b, \) and \( c \). The thicker lines represent distribution via three-phase overhead lines or underground cables. The thin lines inside the community (same color) represent single-phase distribution cables. These cables run from switchgear boxes (identified as switchgear boxes 1, 2, and 3) to each distribution transformer in the form of a circuit loop. It should be noted that each incoming phase from the lateral entrance to switchgear box 1 splits into circuits. These residential circuits, as is common [3], are operated in an open configuration as indicated by dashed lines. For example, phase \( b \) (at switchgear box 1) splits into circuits 2 and 4.

Circuits are protected by 65 A fuses at switchgear boxes, and provide electric service to all single-phase transformers in its path. The primary-side service voltage to each transformer is 7.2 kV (phase to ground) and is stepped down to a usage level 240/120V (split-phase). The group of cables and connections from the transformer secondary-side terminals to each home are collectively known as the secondary distribution network. This secondary network, however, is not shown in Fig. 2.3 and is not modeled in the computer model introduced later. Instead, the secondary network load (including all homes, PVs, and EVs behind the respective transformers) is lumped as an aggregate load for each transformer. This approach was motivated by the analysis and is common practice [4]. In this case the systems of interest were the distribution transformers and the cables feeding those transformers. For this case, including the secondary network in detail would have increased the computational time significantly for little benefit. If there is a subsequent reason to include these networks, the addition is straightforward.

Each transformer is characterized by an identifying number. This number identifies a particular transformer (continuously enumerated from 1 to 94), the phase that serves this transformer (\( a, b, \) or \( c \)), the circuit that this transformer belongs to, and the transformer rating. For example, transformer “T28B2,50” represents transformer #28, is served from phase \( b \), is on circuit 2, and has a rating of 50 kVA.

Each transformer can serve several homes with electric vehicle loads and photovoltaic generation. The information for each transformer was tabulated to show transformer type, number of homes, PVs, and EVs by phase in Table 2-1-Table 2-2. The information changes as the development grows and the power system is modified to efficiently handle the growth.
Therefore the model only reflects the topology at the time of analysis. Since new homes are currently under construction and the acquisition of PVs and EVs continues, accurate counts should be obtained from Pecan Street directly.

![One-line diagram of Mueller Community including 735 homes, 94 transformers, 176 PVs, and 100 EVs (Austin, Texas).](image)

**TABLE 2-1 DISTRIBUTION TRANSFORMER TYPES**

<table>
<thead>
<tr>
<th>kVA</th>
<th>Primary Voltage (V)</th>
<th>Secondary Voltage (V)</th>
<th>No load losses (W)</th>
<th>Loaded losses (W)</th>
<th>Z %</th>
<th>Count</th>
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<td>240/120</td>
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<tr>
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<td>7,200</td>
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<td>683</td>
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<tr>
<td>167</td>
<td>7,200</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>Phase &amp; Circuit</td>
<td>Xfm. #</td>
<td>Xfm. ID</td>
<td>kVA</td>
<td># Homes</td>
<td># PVs</td>
<td># EVs</td>
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<tr>
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<td>--------</td>
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<tr>
<th>Phase &amp; Circuit</th>
<th>Xfm. #</th>
<th>Xfm. ID</th>
<th>kVA</th>
<th># Homes</th>
<th># PVs</th>
<th># EVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>22</td>
<td>T22B2,25</td>
<td>25</td>
<td>3</td>
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<tr>
<td>B2</td>
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<td>T23B2,50</td>
<td>50</td>
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<td>0</td>
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<tr>
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<td>T24B2,75</td>
<td>75</td>
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<td>4</td>
</tr>
<tr>
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<td>50</td>
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</tr>
<tr>
<td>B2</td>
<td>26</td>
<td>T26B2,50</td>
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<tr>
<td>B2</td>
<td>27</td>
<td>T27B2,50</td>
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<td>5</td>
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</tr>
<tr>
<td>B2</td>
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<td>T28B2,50</td>
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<td>B2</td>
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<td>T29B2,50</td>
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<tr>
<td>B2</td>
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<td>T30B2,50</td>
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<td>3</td>
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<td>T31B2,50</td>
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<td>T33B2,50</td>
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<tr>
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<td>T34B2,50</td>
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<tr>
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<td>B2</td>
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<td>B2</td>
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<td>T38B2,75</td>
<td>75</td>
<td>9</td>
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<td>Totals</td>
<td></td>
<td></td>
<td>127</td>
<td>42</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Phase &amp; Circuit</td>
<td>Xfm. #</td>
<td>Xfm. ID</td>
<td>kVA</td>
<td># Homes</td>
<td># PVs</td>
<td># EVs</td>
</tr>
<tr>
<td>----------------</td>
<td>--------</td>
<td>---------</td>
<td>-----</td>
<td>---------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>B4 39</td>
<td>T61B4,50</td>
<td>50</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B4 40</td>
<td>T62B4,50</td>
<td>50</td>
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<td></td>
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<tr>
<td>B4 41</td>
<td>T63B4,50</td>
<td>50</td>
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<td>B4 42</td>
<td>T64B4,50</td>
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<td>1</td>
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<td></td>
</tr>
<tr>
<td>B4 43</td>
<td>T65B4,50</td>
<td>50</td>
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<td></td>
</tr>
<tr>
<td>B4 44</td>
<td>T66B4,50</td>
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<td>B4 45</td>
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<td></td>
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<tr>
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<td>T68B4,50</td>
<td>50</td>
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<td></td>
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<td>5</td>
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<td></td>
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<td>7</td>
<td>3</td>
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</tr>
<tr>
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<tr>
<td>B4 51</td>
<td>T73B4,50</td>
<td>50</td>
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<tr>
<td>B4 52</td>
<td>T74B4,50</td>
<td>50</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>B4 53</td>
<td>T75B4,50</td>
<td>50</td>
<td>10</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>B4 54</td>
<td>T76B4,25</td>
<td>25</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>B4 55</td>
<td>T77B4,25</td>
<td>25</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B4 56</td>
<td>T78B4,25</td>
<td>25</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B4 57</td>
<td>T79B4,50</td>
<td>50</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B4 58</td>
<td>T80B4,50</td>
<td>50</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>B4 59</td>
<td>T81B4,50</td>
<td>50</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B4 60</td>
<td>T82B4,50</td>
<td>50</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B4 61</td>
<td>T83B4,50</td>
<td>50</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B4 62</td>
<td>T84B4,50</td>
<td>50</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B4 63</td>
<td>T85B4,50</td>
<td>50</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B4 64</td>
<td>T86B4,75</td>
<td>75</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B4 65</td>
<td>T87B4,50</td>
<td>50</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B4 66</td>
<td>T88B4,75</td>
<td>75</td>
<td>11</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

| Totals         | 206    | 44    | 23   |
The asset and load counts and ratings for the Muller Community are tabulated in Table 2-3 and Table 2-4, respectively. Table 2-3 lists the asset types, their counts, and the source of the parameters or data. Table 2-4 shows the ratings of each asset type.

**Table 2-3**

<table>
<thead>
<tr>
<th>Type</th>
<th>Count</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homes</td>
<td>735</td>
<td>Data downloaded from TACC(^2) as CSV files</td>
</tr>
<tr>
<td>Photovoltaic Arrays (roof-mounted)</td>
<td>178</td>
<td>Data downloaded from TACC as CSV files</td>
</tr>
<tr>
<td>Electric Vehicles (Chevy Volts)</td>
<td>106</td>
<td>Data generated by randomizing uncorrelated charging</td>
</tr>
</tbody>
</table>

\(^2\) Texas Advanced Computing Center

The asset and load counts and ratings for the Muller Community are tabulated in Table 2-3 and Table 2-4, respectively. Table 2-3 lists the asset types, their counts, and the source of the parameters or data. Table 2-4 shows the ratings of each asset type.
Parameters estimated based on cable length and type

Parameters provided by Austin Energy

<table>
<thead>
<tr>
<th>Type</th>
<th>Load Range (changes every minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homes</td>
<td>up to 10 kW (changes every minute)</td>
</tr>
<tr>
<td>Photovoltaic Arrays (roof-mounted)</td>
<td>up to 6 kW</td>
</tr>
<tr>
<td>Electric Vehicles (Chevy Volts)</td>
<td>0.9 to 3.3 kW (depends on charging level selected randomly)</td>
</tr>
<tr>
<td>Cables</td>
<td>Series impedance estimated based on cable length in feet</td>
</tr>
<tr>
<td>Distribution transformers</td>
<td>Sizes: 25, 50, 75, 100, and 167 kVA. Parameters provided by Austin Energy.</td>
</tr>
</tbody>
</table>

Table 2-4
ASSET / LOAD RATINGS

Fig. 2.4 shows the asset counts (i.e., number of transformers, homes, PVs, and EVs) as percentages. This representation is useful to identify the phase with dominant load and generation. It is seen (consistently) that phase \( b \) has the largest number of transformers, homes, PVs, and EVs.

The information in Fig. 2.4 was grouped to produce single visualizations to better understand the assets per phase. (The analysis of assets on a per-phase basis is important in distribution systems.) These grouped representations are shown in Fig. 2.5 by phase and by circuit. From the top of Fig. 2.5, it is important to notice that phase \( b \) has the most homes (i.e., is the most loaded phase). Additionally, the ratio between PVs and EVs appears to be favorable. This suggests that EV loads may be offset by the larger number of PVs. Any apparent balance or imbalance is likely transitory as the community is developed and the distribution system matures.
Fig. 2.4 Counts and percentages of transformers, homes, PVs, and EVs in each phase
The generation per phase is of particular interest. It was noticed in Fig. 2.5 that most of the residential solar generation is attached to phase $b$. Assuming that the PVs produce 5 kW (peak), the peak generation for each phase (aggregate) is shown in Fig. 2.6. Similar to loads, generation also contributes to unbalancing.
The distribution transformers at Mueller are of four different sizes: 25, 50, 75, 100, and 167 kVA. Pictures of each transformer are shown by Table 2-5. The sizes are shown in upper-left corner of the transformer in yellow letters. The numbering convention used in the model is deliberately different from the convention of the local utility to maintain the privacy of their system. The corresponding transformer impedances are shown in Table 2-6, which were used in the model.

---

3 Not to be confused with the substation transformers.
TABLE 2-5
PHOTOS OF EACH TRANSFORMER SIZE AT MUELLER (PHOTOS TAKEN BY CEM)

TABLE 2-6
IMPEDANCE INFORMATION FOR EACH TRANSFORMER TYPE (COURTESY OF AUSTIN ENERGY)

<table>
<thead>
<tr>
<th>Transformer (kVA)</th>
<th>No-Load Losses (Watts)</th>
<th>Load Losses (Watts)</th>
<th>Impedance (%) @ 85°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>71</td>
<td>228</td>
<td>2.3</td>
</tr>
<tr>
<td>50</td>
<td>105</td>
<td>404</td>
<td>2.3</td>
</tr>
<tr>
<td>75</td>
<td>167</td>
<td>456</td>
<td>2.5</td>
</tr>
<tr>
<td>100</td>
<td>181</td>
<td>683</td>
<td>2.5</td>
</tr>
<tr>
<td>167</td>
<td>248</td>
<td>1234</td>
<td>3.0</td>
</tr>
<tr>
<td>250</td>
<td>373</td>
<td>1555</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Utilities are concerned about the potential impact of EVs on transformers, but are also aware of the impact of PVs in addition to EVs. The simulation results later will show that these transformers, as a result of the PVs, now behave as bidirectional voltage converters (step-down and step-up).

The cost of these transformers is an important parameter in determining the economic viability of community storage [5],[6]. The counts, individual cost, and approximate total investment are shown in Fig. 2.7. From these costs, it appears that capital costs of transformer upgrades are not expensive (replacement man-hour costs not taken into accounted). It should be made clear that these transformer costs are not those of Austin Energy. The total equipment costs for the Mueller neighborhood are based on the cited source.

![Fig. 2.7 Transformer count and approximate cost](image)

Fig. 2.7 Transformer count and approximate cost [7]
3 Software Evaluation

The authors evaluated several candidate software packages before building a computer model of the Muller community in MATLAB/Simulink [8],[9]. The choice of using MATLAB/Simulink came about after several months of understanding what was needed from a simulation tool in lieu of available residential consumption and generation data.

Among the important traits required of a modeling tool was its compatibility (i.e., import capability) to accept the recorded data provided by Pecan Street. Using this recorded data, the candidate software was expected to return the state of the Mueller community. State refers to known levels of voltage, currents, and power flows everywhere in the distribution system presented in the previous chapter.

This chapter presents the evaluation efforts undertaken by the authors to identify MATLAB/Simulink as the software of choice for modeling and simulating the Mueller community. Given that software packages are continuously improving and that this particular task required the import of data in a particular format and widespread use of the software in a university environment, it is not expected that others could use the results of this analysis. It is presented to show the process, which may be useful to others. This is not an endorsement of a single product, as all [10-15] are improving and could be used in closely related situations.

3.1 Simulation Type

After conversing with several utility engineers, consulting companies, and software manufacturers, it was determined that an appropriate simulation type to model the Mueller community was time domain load flow (also known as quasi-static simulation [4]). This simulation type produces a series of power (load) flow solutions in user-specified time intervals. Since Pecan Street made available recorded data in one minute intervals, time domain load flows at the same time intervals seemed to be a compatible simulation type.

A load flow solution pertains to the solution of state of an electric power system computer model. This solution of state returns the voltages at every node, the current in every cable, the power flow into every transformer and load, and the distribution voltage drops and power losses everywhere in the network [16],[17]. When pre-pended with the term time domain, a load flow simulation produces a series of load solutions over time, and allows seeing variations in system state at the desired time interval.

For this project, the simulation time interval was chosen in accordance to the time interval of the recorded data provided by Pecan Street: 1 minute. Therefore, a 24-hour time domain load flow solution of the Mueller community produced 24 h x 60 m = 1,440 load flow solutions. The advantages of this simulation type are its computational speed, compatibility with the data provided, and that it allows the simulation’s inputs to vary with time (as opposed to assuming a constant value for generation and load).

Readers will be likely familiar with time domain electromagnetic transient [18] simulation (also known as transient simulation) [19-21]. This type of simulation produces comprehensive, waveform-level, high-fidelity results. In many research cases, this is the preferred simulation type. The disadvantages of this simulation type are its computational time and the difficulty in obtaining appropriate power apparatus data. Therefore, this simulation type was not considered here. For completeness, a comparison table between (time domain) load flow and
(electromagnetic) transient simulation is provided in Table 3-1. A brief description of the items in Table 3-1 follow:

<table>
<thead>
<tr>
<th>Result Type</th>
<th>Load Flow (frequency domain)</th>
<th>Transient (time domain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time step</td>
<td>1 minute</td>
<td>50 x 10^6 s</td>
</tr>
<tr>
<td>Run time</td>
<td>10 to 20 s</td>
<td>3 to 9 hours</td>
</tr>
<tr>
<td>Simulation time span</td>
<td>days</td>
<td>seconds</td>
</tr>
<tr>
<td>When to use</td>
<td>Early-stage power system design</td>
<td>Later in the design cycle</td>
</tr>
<tr>
<td>Major limitations</td>
<td>Cannot model power electronics</td>
<td>Simulation seed</td>
</tr>
<tr>
<td></td>
<td>Time step is large</td>
<td>Lack of house and PV models</td>
</tr>
<tr>
<td></td>
<td>Dynamics are obfuscated</td>
<td>Cannot simulate for too long</td>
</tr>
<tr>
<td>Major advantages</td>
<td>Speed</td>
<td>Transient detail</td>
</tr>
<tr>
<td></td>
<td>Compatibility Pecan Street data</td>
<td>Can assess voltage fluctuations and stability</td>
</tr>
<tr>
<td></td>
<td>Can simulate days, weeks, and months</td>
<td></td>
</tr>
</tbody>
</table>

**Result Type**

Load flow simulations return voltage and current phasors. These quantities are computed in the frequency domain using complex numbers, and by specifying the fixed frequency of interest (e.g., 60 Hz). Phasors, however, only contain information about their magnitude (root-mean-square, RMS) and phase angle. In fact, from these RMS values, it is not possible to assert whether or not the waveforms are sinusoidal. Phasors do not provide information on the harmonic distortion or transient stress.

Transient simulations, on the other hand, return *instantaneous* voltages and currents. These quantities are computed at microsecond intervals and provide waveform-level detail. From waveform-level results, one can determine whether or not the system voltages and currents are sinusoidal. A screenshot comparing phasor and instantaneous (continuous) values is shown in Fig. 3.1. It should be noted that phasors can be computed from instantaneous values, but the reverse is not true.

**Time Step**

The simulation timestep (or interval) defines how often the simulation's solutions are computed. Since it was determined that load flow simulations were appropriate for this work, the timestep was matched to the timestep of the recorded data provided by Pecan Street (\(\Delta t = 1 \text{ min} = 60 \text{ s}\)).

**Run Time**

Load flow simulations execute faster than transient ones for the same circuit topology. This stems from the total number of solutions required to complete a simulation. For example, a 24-hour load flow solution requires \(24 \times 3600/60 = 1,440\) solutions. A 24-hour transient solution requires \(24 \times 3600/50 \times 10^{-6} = 1.728 \times 10^9\) solutions.
Simulation Time Span

The simulation time span defines the stop time of the simulation. Since load flow simulations execute rapidly, this stop time can be set to 24 hours or 7 days. On the other hand, in the case of transient simulations, setting these stop values to anything more than seconds produces undesirable simulation wait times.

When to Use

Load flow simulation is commonly used early in simulation tasks, because they execute fast, provide high-level results that are necessary to guide further research, and allow for longer simulation time spans. Transient simulations, on the other hand, are normally used late in the modeling or design stage. For example, transient simulations can be used to observe energization inrush currents after it has been decided how many transformers will be installed in a distribution system.

Major Limitations

Load flow simulation does not allow simulating power electronic converters or dc systems. Additionally, because of the fixed-frequency simulation type and large timestep (e.g., 1 min.), load flow results do not show transient-level detail. The major limitations of transient simulations are its speed, lack of high-fidelity models to make results credible, and the imposed restriction of using reduced time spans.

---

Fig. 3.1 Comparison between phasor and instantaneous (continuous) values

**Major Advantages**

Load flow simulations execute rapidly, are compatible with Pecan Street data, and allow for long simulation time spans. Transient simulations provide a high-level of detail and can be used to assess voltage stability concerns [22-25].

**3.2 Software Evaluation**

The authors determined that time domain load flow (using phasors or complex-valued results) was appropriate to model the electric service of the Mueller community and other time-varying renewable sources. The constraints evaluated to down-select the candidate tools follow.

The candidate software requirements included:

- perform offline time domain load flow (not in real time; not a single-solution, static load flow)
- allow for simulation time intervals of $\Delta t = 60$ s = 1 m (not the typical 15 min)
- be reasonably-priced to acquire five licenses
  - 1 for Pecan Street
  - 1 for CEM
  - 3 for UT students
- allow its users to create custom models (e.g., EV charging stations)
- have appropriate documentation, tutorials, and learning paraphernalia
- have a modest learning curve and/or provide free training for its users
- provide phone support
- allow students to share models over email and open them from their own laptops

The above items impose strict requirements on the choice of software that are not always relevant in industrial situations or in situations in which the circuit topology changes slowly if at all. However, considering the costs and learning time associated with software acquisitions, taking these traits into account was necessary.

Several software packages were considered. After a period of surveying the web, contacting utilities and consultants in the United States, scheduling phone calls with software sales associates, and requesting webinars to explore software capabilities and limitations, the four software packages listed in Table 3-2 were the finalists. The evaluation of these software packages included download and installation time, exercising available “walk-throughs” and spending time determining whether they met the selection criteria. The meanings of these metrics (table columns in Table 3-2) follow.
TABLE 3-2
SOFTWARE CONSIDERED FOR THE SIMULATION

<table>
<thead>
<tr>
<th>Name and Version</th>
<th>Cost#</th>
<th>Learning Time</th>
<th>Offline Load Flow</th>
<th>Real Time Load Flow</th>
<th>Custom Models</th>
<th>Support</th>
<th>User Base</th>
<th>Documentation Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETAP 11</td>
<td>$15,000</td>
<td>High</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Paid</td>
<td>More</td>
<td>More</td>
</tr>
<tr>
<td>DesignBase 4</td>
<td>$5,000</td>
<td>High</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Paid</td>
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</tr>
<tr>
<td>CYME 8</td>
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<td>High</td>
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<td>No</td>
<td>No</td>
<td>Paid</td>
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<td>Less</td>
</tr>
<tr>
<td>SimPowerSystems 5.2</td>
<td>N/A*</td>
<td>Low**</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Free</td>
<td>Most</td>
<td>Most</td>
</tr>
</tbody>
</table>

#prices vary by buyer, number of seats, and modules included

*low-cost for students

**familiar to the researchers involved

Name and Version

The table lists, in its first column, the software name and version number (software manufacturer omitted). This shows the software version, as evaluated by the authors. Also, it indicates that the software assessment herein is limited to these version numbers. Software manufacturers constantly improve their products; thus, some of the observations presented will likely be invalid starting 2013. For further reference, an older, yet more complete, software evaluation is available in [26].

Cost

The cost is the dollar amount required to acquire one seat. Whether or not UT or Pecan Street qualifies for software donations is determined by the software manufacturer. Through the several phone conversations with software manufacturers, it was found that some manufacturers considered a software donation to UT, but not Pecan Street; other manufacturers did not consider a donation for neither UT nor Pecan Street. *SimPowerSystems* was the best candidate for this metric because The University of Texas at Austin has numerous departmental licenses for its use and because it is inexpensive for students and professors to install on their personal machines.

Learning Time

The learning time is defined as the time required for users to attain acceptable levels of productivity, the major drawback of acquiring new software. When the project started, there was little experience in modeling and simulation software outside of the *MATLAB/Simulink* environment. Yet, a tool outside this environment was considered a plausible choice. From the learning exercises and training attended, it was estimated that it would take a user six months (at 40% time) to become minimally productive in a new software package. This is a considerable time investment that imposes a significant delay in research results. Since UT researchers were already familiar with the *MATLAB/Simulink* environment, *SimPowerSystems* was elected as the best candidate to circumvent learning time.7

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5 This is not a comprehensive software survey. It is a brief survey of the programs that appear to have the most presence in the utility industry and limited to software features available during fall of 2011.

6 A *seat* is a term used to represent a single license to execute one copy of a software program on one computer. Multiple-seat options are available as well.

7 *SimPowerSystems* is a library of power apparatus models accessible to *MATLAB/Simulink*; users
Offline Load Flow

Offline load flow is defined as the ability for a program to perform time domain load flows offline without requiring hardware acquisitions. This was necessary as it was expected that students and researchers would work from low-cost personal machines. *CYME* was the only product providing this feature through its Long-Term Dynamics analysis module; hence, CYME won this metric.

Real-Time Load Flow

Real-time load flow is defined as the ability of a program to perform time domain load flows in real time—that is, as recorded data is streamed into a software program in real time. The authors were informed by several vendors that streaming Pecan Street’s recorded data would require a Supervisory Control and Data Acquisition (SCADA) system. Since a SCADA system was not available for the project, this metric lost relevance. However, it was noted that (currently) only two products provide this feature: *ETAP* and *DesignBase*. This feature is important in the context of energy management through virtual dashboards, as needed by utilities and control centers (e.g. military installations)—but was not required for the research surrounding Pecan Street.

Custom Models

Software that supports custom models is defined as software that supports the ability for users to create custom power apparatus and/or controller models. While most commercial programs include extensive library of power apparatus taken from catalogs and vendor tables, some modern-day power apparatus are not yet available in the default libraries (e.g., EVs, PVs, or cloud-passage models).

The lack of models mandates creating custom models. Most programs allow creating custom models, but *MATLAB/Simulink* presented fewer limitations to the user in terms of number of building-block types. For example, during the evaluation of one candidate tool, it was found that the number of blocks available to create custom models was limited. Due to the extensive number of blocks required to create custom models and the rich block-library available in *Simulink*, *MATLAB/Simulink* won this metric.

Support

Support is defined as the level of *free* support provided by a software manufacturer. It was found that phone support is normally free for the first year. Given the software learning curve, free support for one year would have been of little value. Since *SimPowerSystems* is part of UT’s maintenance license agreement, students and researches have free access to technical phone support with the *MathWorks, Inc.* (creators of *MATLAB/Simulink*). Therefore, *SimPowerSystems* won this metric as well.

User Base

The user base is defined as an estimate of the number of users knowledgeable in a particular tool. This is important when visiting technical forums online, where the larger the user base, the more likely it is to find answers to a problem. The inability to resolve problems within acceptable time may lead to costly research delays.


Documentation Examples

Similar to the user base, examples and tutorials are important to reduce learning time and work through difficulties. From the online documentation, videos, and available examples, the winner of this metric was SimPowerSystems. SimPowerSystems ships with a large number of examples (similar to other tools); however, it was determined that SimPowerSystems models were also accompanied with a significant level of explanatory text.

From the above comparisons, the software chosen to conduct the simulations for Pecan Street was SimPowerSystems [8]. It is clear from these considerations that the selection was based heavily on the existing situation and is not a general conclusion.
4 Computer Model

Fig. 4.1 shows an annotated screenshot of the top-level view of the Mueller community computer model. This model was created in MATLAB/Simulink using power apparatus models from the SimPowerSystems blockset. The top-level view is consistent with the one-line diagram shown earlier in Fig. 2.3, where the electric service enters from the laterals (substation 1 and 2), shown on the left and right sides of the model. It is important to note that oscilloscope blocks (gray blocks atop), used to monitor intermediate points in the circuit, can be placed anywhere in the network to unveil system state. Observing system state is one of the most important benefits of using computer models to observe current and future system behavior.

Fig. 4.1 Computer of the Mueller community built in MATLAB/Simulink

A screenshot showing phase a, circuit 1 is shown in Fig. 4.2. This circuit consists of a “daisy chain” sequence of loaded distribution transformers interconnected via single-phase cables. (It should be noted that, although circuits can operate closed, they operate in open-loop to increase reliability and to limit down-time during service [3].) The split-phase transformers (7.2kV-240/120V) blocks were taken from the SimPowerSystems library. The cables were modeled as series RX impedance branches, also taken from the SimPowerSystems library. The RX values
for each cable were calculated using estimated cable lengths and aluminum conductor data [1],[7],[27],[28]. (The cable types were shown on the one-line diagram in Fig. 2.3.) A close-up of phase \( b \), circuit 2 is shown in Fig. 4.3. This view elucidates how transformers are served from each circuit, the scopes in front and behind each transformer, and—most importantly—the load-profile block that loads each transformer using the recorded data provided by Pecan Street.

![Fig. 4.2 Mueller community computer model. View of phase \( a \), circuit 1](image-url)
Fig. 4.3 Mueller community computer model. Close-up view of phase $b$, circuit 2

Each of the 94 transformers in the computer model was loaded using residential generation and consumption profiles as shown in Fig. 4.3. An illustration of how this data was made compatible with the computer model is shown in Fig. 4.4.

Fig. 4.4 Transformer load model accepting the recorded data provided by Pecan Street

\[
\begin{align*}
\text{Step 1:} & \quad \text{Read terminal voltage phasors for each leg (available from simulation)} \\
\text{Step 2:} & \quad \text{Compute net grid power demand} \\
\text{Step 3:} & \quad \text{Split grid demand in two phases using a random scalar } r \in [0, 1] \\
\text{Step 4:} & \quad \text{Compute current sink phasor for leg 1 } (I_{\text{grid1}}) \quad \text{(repeat for leg 2)} \\
\text{Step 5:} & \quad \text{Apply injections in each leg and advance simulation} \\

V_{\text{grid1}} & \Rightarrow I_{\text{grid1}} \Rightarrow S_{\text{grid1}} \\
V_{\text{grid2}} & \Rightarrow I_{\text{grid2}} \Rightarrow S_{\text{grid2}} \\

\sum P_{\text{homo}} + jQ_{\text{homo}} & \Rightarrow \text{Sum of all residential PV power generation behind transformer} \\
\text{Sum of real and reactive power consumption of all homes behind transformer (including EV charging)} \\

S_{\text{grid1}} = V_{\text{grid1}} I_{\text{grid1}} = r \left[ \left( \sum P_{\text{homo}} + jQ_{\text{homo}} \right) - \sum P_{\text{homo}} \right] \\

7.2 \text{ kV} : 240 \text{ V}
\end{align*}
\]
Referring to Fig. 4.4, as the simulation executes, the voltage at the consumer side of each transformer becomes available (step 1). The power profiles provided by Pecan Street are combined in step 2; that is, residential consumptions and EV charging are summed and PV generation is subtracted from this sum. After computing the total power demand behind each transformer, and since the power distribution in each leg is unknown, a random variable between 0 and 1 is used to split the residential grid demand into the two legs. After dividing the power across the two legs, the current sink value (a complex number) in each leg is computed in step 4. The current sink values are used at the next simulation timestep to draw corresponding complex-valued current in each leg of the secondary-side of the transformer.

This simulation approach of using recorded data together with a computer model to forecast system state elsewhere in the network gives realistic results because the system load is driven by recorded data (PV and residential consumption). For computational efficiency, all homes and PVs at the consumer side of each transformer were lumped into a net single-load equivalent [4]. This load aggregation permitted simulating 735 homes in reasonable time.

A note on how EV charging was modeled is important. Pecan Street collected the charging profile for a Chevy Volt during Spring 2012. The recorded data was made available to the authors and is shown in Fig. 4.5. This figure shows the charging power consumption for the three possible charging levels: slow, normal, and fast. The data was recorded starting from a near-zero state-of-charge in each case. To predict the impact of electric vehicles on residential load, the plug-in time, charge duration, and charging level were all randomized during simulation.

![Fig. 4.5: Chevy Volt charging profiles (1-min. interval) collected by Pecan Street.](image-url)
5 Case Study

The results on the impact of high concentrations of residential PVs and EVs on the distribution transformers were obtained using data provided by Pecan Street (collected at one minute intervals) and the computer model introduced earlier in this report. The data was used as load shapes (i.e., kW vs. time) for both residential consumption and residential generation (PVs). The computer model accepted these load profiles to estimate the voltage, currents, active power, reactive power, and power factor everywhere else in the network (from lateral service entrance to the secondary-side terminals of each distribution transformer). The use of realistic (collected) data together with the computer model allowed for low-cost, fast assessments of the system state.

5.1 Residential Load

Fig. 5.1 shows the power consumption profiles for the 735 homes. These profiles exclude electric vehicle charging and PV generation. The meaning of each view in the figure is explained next:

a) This view shows the active power consumption (kW) of all homes over a 24-hour period. The data is graphed using a mesh grid to produce a 3-D surface plot. The color map corresponding to this surface appears on the right side of the figure, where power consumptions > 10 kW appear in increasingly-dark red color. The advantage of this view is that it permits detecting correlation in consumption behavior by observing the peaks and valleys on the surface. For example, consider the encircled areas of this view. Each area encloses a different group of homes at similar times of the day (~12 PM through 12 AM). The top circle encloses several residences exceeding 10 kW (simultaneously), while the lower circle encompasses other residences going through consumption valley below 4 kW (during the same times of day). These areas suggest that individual residential loads are heterogeneous and their behavior is rather difficult to predict and generalize. Larger scale averages, however, tend to be consistent.

b) This view is a contour plot of the data in (a), and is convenient to shows load durations. For example, referring to the encircled areas corresponding to view (a), the 10 kW peaks do not last long (i.e., only a few minutes). Similarly, the lower encircled area, in this view, shows that the valleys of ~4-5 kW last much longer than the 8-12 kW peaks do. Additionally, not all homes incur such peaks; only some do which is clearly noticeable from this type of view. Also, the dominant color on this contour plot is dark blue. This color suggests that, most of the time, the residential consumption is near 2 kW.

c) This view shows the home consumptions of (a) (same as (b)) as seen from the time-kW plane. Although it is common belief (also an expectation) that all residences in the same community behave in unison in the evening hours, the 735 load shapes suggest there is a high degree of un-correlation in residential load patterns. This behavior is desirable from the utility perspective as transformer loading tends to be closer to an average than the sum of the peak demands. This shows that any pricing or other signals that tend to correlate demand may have an adverse effect on transformer life by stimulating longer operating times at higher temperatures [29]. On the other hand, this independent load behavior makes it difficult to forecast load demand and behavior on a “per-home basis.” It also interesting to note that the average consumption over 24 hours for the 735 homes (computed in time
intervals of one minute) is 0.95 kW. This value is not predicted, modeled, made up, or based on the consumption of a few homes. This value was computed from actual recorded data in one minute intervals, which raises confidence in the result. However, this average value varies by day of the week, time of the year, and is not general.

d) This view aggregates (sums) the power consumption of all homes and approximates the total demand (excluding EVs, PVs, and distribution power losses) as seen from the lateral service entrance. The power is shown decomposed into its real and reactive components. In addition, the power factor is plotted against the right-side axis which is close to 0.9. This power factor is not the same as the power factor seen at the home level. This aggregate power factor is the ratio of real (W) and total power (VA). As noticed from the real and total power traces, the peak power demand occurs in the evening (as expected). In contrast to (c), which is shown at the individual home level, in this lateral-side view, the power consumption profile is repeatable, predictable and—ironically—composed of unpredictable, uncorrelated home consumption profiles. As noticed from the peak total power, the peak load of this community varies between 1 and 1.5 MVA, and also varies by day of the week and time of the year.

Fig. 5.1: Residential demand for 735 homes in a 24-hour period (data interval: 1 minute).
The energy consumption (kWh) corresponding to the load profiles of Fig. 5.1(c) is shown in Fig. 5.2. The left side shows the total energy consumed by each home over the 24-hour period. It can be seen that the peak energy consumption of one home exceeds 80 kWh, but this is uncommon. Most homes, consistent with the average power consumption of ~1 kW shown in Fig. 5.1(c), have average energy consumptions of 24 kWh per day. This averaged value is shown as a red horizontal line.

The right side of the figure shows the distribution (grouping) of energy consumption. The number of homes consuming 15 kWh is 44, which is the largest group of homes consuming the same amount of energy per day. Neighboring groups within a standard deviation consume 10-30 kWh, which is consistent with the 24 kWh average shown on the left-side chart. As seen from the far right of this chart, very few homes consume >60 kWh. The value in assessing energy consumption per day is valuable to load forecast, growth, and to size residential- and community-level energy storage devices.

Fig. 5.2: Residential energy usage for each home (24-hour period). *Left:* average energy usage for each home and across all homes (23 kWh). *Right:* energy consumption distribution showing that most homes consume 15 kWh per day.
5.2 PV Generation

Fig. 5.3 shows the generation profiles of roof-mounted, residential PV arrays. It should be noted that these grid-tied residential PVs only produce active power, and not reactive power [30],[24]. This contributes to low power factors seen from the lateral service entrance as discussed later.

The meaning of each view of the PV generation views is explained next:

Fig. 5.3: Solar generation for all 178 PVs in a 24-hour period. Data interval: 1 min.

a) This view shows the individual real power generation output of all PVs as a 3-D surface. The color map corresponding to this surface appears on the right side of the figure, where generation > 4.5 kW is indicated in increasing-dark red. This view clearly shows that the peak generation of each residential PV can be similar, but not the same. It is also recognized that the envelope of this surface follows a consistent pattern similar to what is known as the normal (or Gaussian) distribution curve. The encircled area shows a group of PVs with irradiance deficiency. The impact of PV sources with respect to physical characteristics such as rated power, number of cells, connection method, dimensions, cell technology, irradiance based on sun’s azimuth and zenith angles, system efficiency, dynamic variations in atmospheric and environmental air mass, passing clouds inducing whole or scattered shaded areas, and temperature affect the observed power output. Not all PVs are affected by these characteristics the same way due to the geographical separation of
the PVs. Several PVs, for example, appear to be unaffected by these consideration as they output rated power. Unequal irradiance highlights an important fact of distributed generation: not all PVs are affected simultaneously by every cloud event; many PVs retain high power outputs while many others do not. This lack of correlation is advantageous in terms of voltage stability [25] when compared to concentrated PV plants [22-24].

b) This view shows the data in (a) as seen from the top. The encircled area corresponds to the encircled area in view (a), and shows the duration of the aforementioned irradiance deficiencies (6-11 AM). This view also helps counting the number of PVs affected by this deficiency (PV #120 through #140). Another advantage of this view is that it permits comparing the generation profiles of south-facing and west-facing PV arrays. Necessary irradiance reaches south-facing PVs hours before it reaches west-facing PVs. This is opportune for morning loads power by south-facing PVs, and also indicates that west-facing PVs are more aligned with the early-afternoon and evening loads. This is an important consideration to reduce evening demand. Furthermore, the homes at Mueller have either west- or south-facing PVs, or a combination of both west- and south-facing PVs. The disadvantage of dividing the orientation is reduced available or excess power and the reduced ability to sell this power to the utility; the advantage, however, is wider temporal coverage for its owner and correspondingly less temporal dependence from the utility. From the color map on the right, the predominant output power of the PVs is closer to 4 kW than it is to 5 kW, which corresponds to the shoulder hours of the peak irradiance time: 12:45 PM.

c) This view more-clearly shows the lack of correlation in residential PV generation, which is observed even for PVs in close geographic proximity. If the affected PVs are in physical proximity, the PVs will reduce their output in unison to cloud passage. If the PVs are more separated, their output reduces sequentially from one PV to the next. However, these results are not general: they depend on cloud type, height, time of year, and the factors mentioned for view (a) which lie outside the scope of this study. The advantage of having recorded PV data is that irradiance intermittency, due to cloud-passage, is not required as part of a model to observe these effects. Instead, these PV power profiles are injected directly into the computer model using time steps of 1 minute. The method of using recorded data injection as the loads or PV sources, in addition to elevating confidence, allows examining voltage profiles in other parts of the network. Having observable system state allows assessing the effect of PV fluctuations over a wider area if desired.

d) This view shows the aggregate residential PV generation. Although the individual PV generation is intermittent and uncorrelated (as shown in (c)), at the aggregate level, the generation follows a predictable smooth envelope that reaches nearly 0.5 MW per day. The aggregate generation, however, is less than the total residential load shown earlier by the real power (blue) curve in Fig. 5.1 (d). This result indicates that, while this community has a high density of PV generation, no excess PV power exists that can leave the community through the lateral service entrance; instead, this power remains inside the community and consumed as billable energy (kWh) by homes not equipped with such arrays. Customers are credited on their electric bill for 100% of the kWh produced by their solar system at a Value-of-Solar Factor (currently $0.128 / kWh). Therefore, opportunities for energy storage under said tariffs may be limited. On the other hand, this price structure is opportune for PV owners looking into reducing the payback period and commensurately reducing energy bills.
5.3 Electric Vehicles

Fig. 5.4 shows the charging profiles for 100 Chevy Volts. The charging profiles include a realistic mix of 120 and 240 V charging profiles, which is observed in practice. These data are for actual charging profiles, but the analysis was done prior to large-scale installation at homes. Therefore, this analysis is only a prediction of the effect on the system after the roll out of vehicles within the Austin Energy rebate is completed. The meaning of each view is explained next.

**Fig. 5.4**: Charging profiles for all 100 electric vehicles in a 24-hour period. Data interval: 1 min

a) This view shows the load consumption of all electric vehicles using a surface plot. The corresponding color map is on the right of the figure. The peaks of the curve show groups of vehicles charging at 240 V; the lower peaks show charging at 120 V. The mix of high and low peaks is a direct result of randomizing the charging profile levels. The vehicles charging at 240 V appear in red, which corresponds to charging levels of 3.3 kW. The lower peaks corresponding to 120 V appear in cyan and correspond to a charging level of 1.44 kW. There is also a set of vehicles that charge at 0.96 kW, and appear as light blue.
peaks. It should be noticed that the plug-in times were randomized \( \geq 4 \text{ PM} \) for two reasons. First, to exacerbate evening-time charging and assess the potential impact this has on the distribution transformers. Second, plug-in times of \( \geq 4 \text{ PM} \) reduce electrical overlap with PVs.

b) This view shows the plug-in time assumption (\( \geq 4 \text{ PM} \)) by showing charging time spans. The time spans show how long each vehicle charges, which is also random (i.e., based on a random state-of-charge at plug-in time). Some vehicles charge over night and into the early morning hours as shown by the encircled area. These vehicles charge at 120 V and charge at 0.96 kW or 1.44 kW. The short time spans shown in this view represent both 240 V charging (\( \leq 3.5 \text{ hours} \)) and 120 V charging (\( \leq 9 \text{ hours} \)). In the 120 V case, short time spans represent vehicles with a high state-of-charge at plug-in time.

c) Similarly, as shown for residences and PVs, this view shows uncorrelated EV charging. Uncorrelated charging is desirable from the utility standpoint as it circumvents sizing transformers linearly with the expected number of EVs. Uncorrelated power demand is not new; it has been observed for decades in residential air-conditioner usage: many units operate simultaneously (~5 kW), while many do not. The time spans in this view are further annotated with labels showing the three possible charging levels in Chevy Volts, and their maximum (not actual) charging duration. It is noted that 240 V charging requires level-2 chargers and a stand-alone 240 V feeder circuit inside a residence.

d) This plot shows the total EV impact at the lateral level (assuming the uncorrelated charging in view (c)). The EV impact occurs between 6-8 PM and appears to be < 200 kW for a typical day. This forecast is strongly dependent on the degree of correlation included in the model, and is consistent with recent field observations made by Pecan Street. The risk that EV charging presents to utility assets (in particular, distribution transformers) depends on the assumed transformer sizes, number of EVs per transformer [31],[32], and charging levels. As opposed to older communities served from pole-mounted 25 kVA transformers, the transformers at Mueller are generously sized and are able to meet the load incurred by the Chevy Volts. This result is not general. It does not apply to all communities and is based on the assumed charging profiles showed herein. Nonetheless, the result applies to the Mueller community because the recorded data is from the same community and because the transformers are currently underutilized.

5.4 Transformer Impact

Local utilities commonly express concern about the fast growth and impact of the high-levels of residential photovoltaic generation and electric vehicles on a single feeder. This concern stems from uncontrolled distributed generation growth, their uncontrolled placement (electric phase and geographical), and the weather-dependent presence of these assets. The utility’s concern also stems from asset management in the general sense, but in this work, it focuses on the state of health of the distribution transformers. This concern has lead to uncertainty in whether transformers were operating at capacity before the installation of PVs and EVs and whether or not replacement or energy-storage action is needed in the near term.

To help answer these questions using the collected data, the following analysis estimates the real power flow experienced by the transformers and reports their estimated operating conditions. The real-power analysis shows net flow (i.e., forward or reversed) as result of the PV generation.
The total-power analysis shows transformer usage levels due to existing load, PV generation, and electric vehicle charging.

### 5.4.1 Real Power

Using the same presentation conventions as in the previous figures, Fig. 5.5 shows the net real-power flow through each of the 94 distribution transformers.

a) This view shows the net power flow through each transformer measured looking into the primary-side terminals (in the forward or step-down direction). The transformers are enumerated 1 through 94 in accordance with Table 2-2. For example, transformers 1-21 belong to phase \( a \), circuit 1; transformers 22-38 belong to phase \( b \), circuit 2, and so on. The corresponding color map is on the right side of the figure. As noticed from the larger lower encircled area, many transformers experience diurnal reverse (negative) real power flows of \(-12 \text{ kW}\) due to higher PV-to-load ratios. Power reversal is observed on several transformers, but not all. It depends on the time of day (and time of year [33]), weather conditions, and on how many residents have unused PV power. Similarly, the smaller encircled area shows transformers experiencing peak loads of \(~40 \text{ kW}\) in the evening hours. This view, similar to the (a) view of the residential consumption, helps finding similar behavior in transformers via swells and sags in the surface.

b) This view highlights times when transformers experience reverse flows. From the darker blue regions (vertical circle) it is inferred that reverse flows occur on many transformers between 8 AM and 4 PM. These flows are aligned with diurnal PV output, but vary by transformer. The horizontal circle shows some transformers loaded at \(~40 \text{ kW}\). These transformers correspond to T31B2,50 (50 kVA) through T37B2,100 (100 kVA), which shows that these transformers operate below capacity. The dominant color on this contour plot is cyan, which suggests that the typical transformer usage at Mueller is about \(7 \text{ kW}\).

c) This view shows the load profiles for all transformers, which includes residential load, PV generation, and EV charging. It is clear from this view that several transformers act as step-up transformers due to the excess PV generation. This excess power flows back into the grid and is consumed by neighboring transformers on the same phase. As shown by the solid line, the average transformer load is \(~7 \text{ kW}\). This value is the average transformer load for 94 transformers over 1,440 minutes (24 hours). The expected peak and average provide useful information to size community-energy storage units intended to operate along-side distribution transformers. (The topic of the next progress report by the authors.)

d) This view shows the aggregate transformer load; that is, the load-sum of all 94 distribution transformers as seen from the lateral service entrance. This load includes the residential load, PV generation, and EV charging from all transformers. As expected, peak consumptions occur during breakfast and dinner times. Interestingly, these peaks are separated by a significantly-low diurnal demand when PVs are mostly active. This low demand is a direct result of having a high concentration of PVs on the same service lateral.
5.4.2 Total Percent Utilization

Although Fig. 5.5 shows the direction of real power flow through each transformer, it does not convey transformer-utilization information. Consider Fig. 5.6, which shows the utilization (in %-VA) of each transformer. For example, a 50 kVA transformer drawing 5 A at 7.2 kV is 72 % utilized ($7.2 \text{ kV} \times 5 \text{ A} = 36 \text{ kVA} \Rightarrow 100 \times \frac{36}{50} = 72 \%$). Following this definition, an explanation of each view in Fig. 5.6 follows.

a) This view reveals that some transformers are ~90 % utilized, but not all of them. These few transformers, however, do not experience sustained loads at these levels. Instead, this loading condition is intermittent. It should be noticed that the diurnal %-utilization accounts for PV real power throughput in the reverse direction (if any) and the reactive power demanded by the residences.

b) This view shows the duration of the high-load conditions. It also confirms that this loading is intermittent. The dominant color in this view is dark blue, which indicates that most of the time the transformers operate between 10-30 % of their rated capacity. This view shows the load profiles (VA) of all transformers. The average transformer consumption over the 24-
hour period analyzed in this work is 14.6%. This percent-utilization is consistent with the surface level in (a) and dominant color in (b). Additionally, this view also shows that there is an uncorrelated transformer load. It should be noted that this view is different from Fig. 5.5(c) in that transformer utilization, in %-VA, is always positive.

c) This view shows the aggregate transformer throughput (W, Var, and VA) as seen from the lateral service entrance. This power throughput includes transformer losses (core and conduction), residential load, PV generation, and EV charging. The figure shows a trace for the power factor against the right-side axis. The power factor trace shows poor diurnal power conditions due to excess PV generation in this community. As seen between 11 AM and 2 PM, the utility supplies nearly the same amount of reactive power as it does real power. During these times, the utility experiences power-factor conditions as low as ~0.6. This power factor condition, however, is only observed from the lateral service entrance and is not necessarily the case as seen from the feeder head or substation transformer.

Fig. 5.6: Percent-utilization of all distribution transformers

5.4.3 Transformer Voltage Profiles

Fig. 5.7 show the secondary-side voltage profiles of all transformers using two views. The left side shows the profiles over time and in per-unit using 94 traces (one per transformer). As
observed in the diurnal hours, PVs produce voltage swells transformer above 1.0 pu (on a 240 V base) for several transformers, however, this voltage swell is minor. Also, from the left-side view, EVs lower the transformer voltage during the evening hours. Both situations, however, appear to be of minimal, if any, significance.

![Fig. 5.7: Transformer voltage profiles (secondary side)](image)

The impact of PVs and EVs on distribution transformer voltage is explained by referring to the transformer percent impedance (Z %) nameplate values listed in Table 2-6. The Z % value of a transformer has several meanings [34]. The meaning of interest here is the one that approximates (in %) the voltage drop across the transformer series impedance under full-load current. As learned from Fig. 5.6(c), most transformers do not operate at capacity (or full-load current); henceforth, their voltage drop is less than the nameplate Z % value—even with the high concentrations of PVs and EVs modeled herein.

The right side of Fig. 5.7 shows a filled 2-D contour representation of the same voltage profiles. The dominant color is yellow, which indicates that most transformers (most of the time) operate at values near 240 V. (The color map is shown on the right side of the figure.) The encircled regions show the times of the day where the transformer voltages are highest. Voltages >1.0 pu are due to PVs producing localized power, which reduces transformer through current and voltage drops. Similarly, in the afternoons, the filled contour plot exhibits darker regions corresponding to lower voltages due to EV charging.
5.4.4 Transformer Utilization: Before and After

It is interesting to visualize transformer usages before and after the penetration of PVs and EVs. Such visualizations help answer the common question of *what are PVs and EVs doing to the (distribution) transformers?*

Fig. 5.8 shows the transformer utilization (in %-VA, 1-min. intervals) for the distribution transformers over a 24-hour period. The left side of the figure shows transformer utilizations *before* the addition of any PVs and EVs (i.e., utilization strictly due to residential load). These are calculated results using the models that have been developed. As noted from the corresponding color map, all transformer utilizations are >0 %. This indicates that power flows through each transformer in the forward direction: from utility to residences. The encircled area on the left side shows transformers 30 through 35 experiencing a high load (~90 %) with respect to their power rating. This is an indication that these transformers will likely be impacted first by the penetration of EVs (if any are served from these transformers).

The right side of the figure shows the transformer utilization after PVs and EVs are added to the model. In contrast to the left side of the figure, the right side shows negative utilizations (< 0 %). Negative consumptions indicate that the power flows from residences to the grid. For example, consider the encircled region for transformers 19 through 35. Referring to the color map on the right, these transformers experience negative flows of -20 % as indicated by their dark blue color. This indicates that these transformers inject power into the grid at 20 % of their capacity. The squared area shows the impact of EVs. When compared to the left side of the figure, the square area shows an increase in transformer utilization. This utilization increase, however, is minor with the limited number of EVs.

For transformers serving EVs, the impact on them is small for three reasons: 1) the transformers are sized appropriately, 2) EVs do not charge in unison, and 3) not all EVs charge at 240 V. It should be noted that only real power reverses as PVs do not produce reactive power.

Additionally, total power $S$ (VA) does not convey sign information. The sign of $S$ is borrowed from $P$ (real power) for clarity; henceforth, $r = \pm 1$, represents the direction of the active power, and is appended to $S$ to convey utilization directionality.
5.4.5 Change in Transformer Utilization

Although the filled 2-D contour plots of Fig. 5.8 contrast transformer use before and after the inclusion of PVs and EVs, they do not quantify the change. Fig. 5.9 shows the change using two approaches. The left-side view quantities change as the absolute value of the arithmetic difference of before-and-after power through the transformer. This arithmetic difference is calculated as $\Delta S^\% = S^\%_{\text{after}} - S^\%_{\text{before}}$, where $\Delta S^\%$ represents the percent-change of interest, $S^\%_{\text{after}}$ represents the %-utilization (VA) after the inclusion of PVs and EVs, $S^\%_{\text{before}}$ represents the %-utilization (VA) before the inclusion of PVs and EVs (always a positive quantity), and $r$ represents the direction of the real power flow.

Referring to the circled areas on the left of Fig. 5.9, it is clear that PVs and EVs alter transformer utilization. These changes have $+$ or $-$ signs associated with them according to the color map (%) immediately to their right. The signs indicate whether PVs increase or decrease transformer throughput. Although it is commonly believed that PVs reduce transformer
throughput, PVs also increases it. The encircled areas show examples of when PVs reduce transformer throughput (blue color, < 0 %), and when PVs increase transformer throughput (yellow to red colors, > 0 %). These percentages do not indicate percent utilization; they indicate percent change.

For example, consider any transformer in which the forward %-utilization before was $S_{\text{before}}^{\%} = 20\%$. This value will always be >0 % because residential consumption is always from grid to residences. Further consider that after the installation of PVs behind the same transformer, the utilization changes to $S_{\text{after}}^{\%} = 10\%$. The %-change in transformer utilization is then $\Delta S^{\%} = 10\% - 20\% = -10\%$. The value of -10 % indicates that this transformer is, as a result of the PVs behind it, utilized 10 % of its capacity. The negative sign indicates that the utilization has reduced from what it was before. As another example, if the %-change in another transformer’s utilization was $\Delta S^{\%} = 45\% - 20\% = 25\%$, this would indicate that the transformer is now used more than before as a result of its residential PVs. In such situation, it is said that PVs increase transformer utilization. Referring back to the left of Fig. 5.9, all regions >0 % (light green through red) show increases in transformer utilization. Similarly, all regions <0 % (light green through dark blue) show reductions in transformer utilization. The regions at 0 % (light green) indicate that during these times of the day, transformer utilizations exhibit noticeable changes. In fact, most of the area on the left-side view is in the vicinity of 0 %. This suggests that not all transformers have PVs and EVs, and that if they do, during the hours shown in light green, the change is not apparent.

The view on the right quantifies change as the ratio of before-to-after utilization. This ratio is calculated as $\Delta S^x = S_{\text{after}}^{\%}/S_{\text{before}}^{\%}$, where $\Delta S^x$ represents the per-unit change in utilization, $S_{\text{after}}^{\%}$ represents the %-utilization (VA) after the inclusion of PVs and EVs, and $S_{\text{before}}^{\%}$ represents the %-utilization (VA) before the inclusion of PVs and EVs.

Values of $0 < \Delta S^x < 1$ indicate transformers are used less than before. For example, a value of $\Delta S^x = 0.2x$ indicates a transformer is used five times less than before. Similarly, values of $\Delta S^x > 1$ indicate transformers are used more than before. For example, a value of $\Delta S^x = 3x$ indicates a transformer is used three times more than before. It should be noted that these utilization changes are typically of short duration; that is, they only last for a few hours at most, not all day. As seen, the dominant color is dark blue (~1x). This result indicates that most of the time, the %-change of transformer utilization does not change.

The enclosed areas (same as on the left-side view) show which transformers are utilized less (or more) than before. For example, the top encircled area (on the right) shows that some transformers (transformers #68 through 84) are utilized one half what they used to. The lower circled region covers several transformers having a peak use of 300-400% more than before. However, these changes are not sustained; they are present when PVs are fully illuminated and for those transformers that have more PV generation than residential load. This reversal can increase the transformer utilization for several hours. The square area shows the impact of EVs on select transformers. This area, for example, shows that EVs can increase transformer utilization by 10 % during the evening hours.
5.5 Lateral Analysis

This section shows the impact of PVs and EVs as seen from the lateral service entrance. This view is the last view

5.5.1 Power Breakdown

Fig. 5.10 shows a breakdown of the aggregate power profiles for the residences, PVs, and for the EVs. The net difference between the total consumption (residential and EVs) and PV generation is the net power delivered by the utility. This net grid power shows a significantly diurnal reduction in proportion to the aggregate PV generation, which is power not sold by the utility. It should also be noted that, as seen from the lateral service entrance to the community, the total PV generation is less than the power demand. This means that the PV generation is trapped inside the community and does not leave into the feeder lines. Thus, the impact of PVs is localized to transformers rather than seen at the circuit, lateral, feeder, or substation levels.
5.5.2 Power Demand

Fig. 5.11 shows the total consumption of the community consumption in terms of apparent, real, reactive power including distribution losses (due to cables and transformers), and power factor. The power factor, which refers to displacement power factor rather than total power factor [35], is plotted against the right-side axis. This active power trace is larger than what was shown earlier in Fig. 5.6(d) due to the inclusion (now) of transformer and cable conduction losses. Comparing the left (before PVs and EVs) and right (after PVs and EVs), the most appreciable change is the reduction of real (active) power demand. The diurnal real power demand is approximately 600 kW. After the inclusion of PVs, the power demand from the utility to service the same load is reduced to about 200 kW. The effect of low power demand is appreciable (and common [36]). As noticed during the high irradiance hours, the power factor experienced by the utility reduces to ~0.6 as grid-tied solar systems only provide real power. Consistent with this observation is that reactive power is still provided from the grid. That is, residences rely on the utility providing reactive power although the utility cannot bill for this service. This has two implications: first, residences cannot become grid-independent until they overcome their dependence on reactive power; second, since the utility is required to meet a power factor of 0.97 at the substation (per ERCOT guidelines) additional reactive power must be provided on the feeders, not at the generation facilities. This will require additional capital investment that the utility cannot recover from residential customers, so all ratepayers contribute. schedule generation to provide reactive power even though the utility cannot bill the customer for it. There are jurisdictions abroad that specify that the inverters on PV systems must supply both real and reactive power [36].
5.5.3 Lateral Current

Fig. 5.12 shows the current in each phase of the main lateral service entrance. The left- and right-sides show the currents before and after the interconnection of PVs and EVs, respectively. The top and bottom charts (in each figure) show the %-unbalance and average current. The current unbalance (%) was calculating using (5.1). Current unbalance is the maximum deviation from the average of the line current divided by the average current.

\[
I_{unb} = 100 \times \frac{\max (dI_a, dI_b, dI_c)}{I_{avg}} \%
\]  

(5.1)

- \(I_{unb}\): Current unbalance (%)
- \(dI_a\): Deviation of phase a current avg. current (A)
- \(dI_b\): Deviation of phase b current avg. current (A)
- \(dI_c\): Deviation of phase c current avg. current (A)
Significant current unbalance can produce voltage unbalances at the service terminals of other three-phase customers on the feeder. The unbalance is caused by the uneven presence of single-phase residential load and PV generation on three-phase systems. In addition, the unbalance is caused by a utility’s inevitable inexactitudes of load forecast and by interconnection-ease accessible to field line-men.

Comparing the current unbalance before and after the installation of residential PVs, it is seen that PVs can re-balance the line currents—but not by virtue of active control, but by virtue of decreasing the unbalanced demand instead. Therefore, the combination of existing voltage unbalance in the system due to uneven single-phase load distribution and uneven single-phase PV generation may contribute to unacceptably high unbalance levels. If there is significant current unbalance at the lateral level, it may produce unbalance voltage levels along the feeder that may exceed recommendations [37],[38]. At this time it is not possible to make this determination because the load profiles, topology, and line impedances upstream of the main service lateral are not known to the authors.

Referring to the current in phase $b$ (before and after), it is seen that there is a growth in demand due to the EVs. Also, there is a significant diurnal reduction. The latter stems from the multitude of PVs connected on phase $b$ when compared to the reduction in phases $a$ and $c$. Referring to the unbalance on the lower charts, the presence of PVs reduces the diurnal unbalance. During the evenings, EVs do not increase the unbalance because of uncorrelated charging, charging levels, times, and number of EVs per phase. This latter result is somewhat interesting, as it is commonly believed that EVs are detrimental to feeder service. Apparently, from the results and at the level of penetration, EVs charging is benign. However, these conclusions are limited to the observations over a 24-hour period. More general conclusions may be derived using yearly data, which is not yet available.

The detrimental effects of unbalanced service voltage are well known. These include uneven voltage levels which can cause sensitive equipment to trip, over-heating of the neutral conductor which is sized to carry the maximum-likely unbalance [27], uneven distribution losses, heating in machine-based equipment, and a possible wide-area decrease in service quality. In order to prevent problems caused by unbalanced voltages, single-phase loads are connected evenly across all three phases, i.e., future loads from the highest loaded phase should be planned for the other two phases. Furthermore, for the lowest cost electric utility, PV resources should—ideally—be interconnected to the highest loaded phase; however, utilities do not have the authority over residents to dictate this.
5.6 Distribution Losses

Fig. 5.13 shows the power distribution losses on cables, transformers, and their sum. The left- and right-sides, respectively, show these losses before and after the inclusion of PVs and EVs.

Referring to the cable losses (top chart in each column), it is seen that the PVs reduce the diurnal losses as there is current demand. For example by 4 PM before PVs and EVs, the $-losses were about $1. The inclusion of PVs reduced this value to nearly $0.5. The monetary value is insignificant for two reasons: the current at 12.47Y/7.2 kV is low and the potential billable losses are based on the assumed (and rounded) rate of $0.13 / kWh. In the evening hours between 6-10 PM, the $-losses increment more rapidly due to the EVs. However, because the daytime losses were reduced, and the nocturnal losses increased, the end result is “a wash.” The $-losses at the end of the day are near $2 before and after the inclusion of PVs and EVs.

Referring to the transformer (conduction) losses (middle chart in each column), it appears that there is no change during the daylight hours. This result is the added losses of all 94 transformers. That is, some transformers experience less loss due to PV-induced power flow reversals while other transformers experience an increase in reverse power flow. Comparing the before and after transformer losses, the aggregate result is unchanged. During the evening hours, the EVs increase the power losses some, but not much. At the end of the day, the $-losses are similar as well.

The total (cable and transformer) losses are shown on the bottom row. The minor differences stem from the cable losses, which although small, show that daytime losses are reduced while...
evening losses are slightly increased. At the end of the day, $-losses before and after PVs and EVs is ~$36 in each case. Interestingly, it appears that the reduction in losses due to PVs and increase in losses due to PVs and EVs cancel out and result in “a wash.”

Fig. 5.13: Cable, transformer, and total distribution losses in watts and dollars. *Left:* before PVs and EVs; *Right:* after PVs and EVs)
6 Conclusions

It was determined that time-domain load-flow was a suitable approach to simulate the electrical service of the Mueller community. This result stemmed, principally, from three reasons: computational speed, compatibility with recorded data, and the difficulty (otherwise) of obtaining power apparatus parameters for time domain (electromagnetic transient) simulations.

The authors used MATLAB/Simulink and the SimPowerSystems blockset to build the computer model of the Mueller community. This choice came about after evaluating other commercial options. The choice was driven by the accessibility of user support, the ability for UT students to create custom models (e.g., energy storage modules, or EV chargers), and by the ability for UT students to have this software installed on their personal computers. Another metric considered was learning time. Software learning-time is detrimental to timely research efforts such as the ones presented here. Additionally, this platform is not solely for electrical engineers. It is also a preferred choice in other engineering disciplines (e.g., mechanical engineering), which is consistent with the multi-disciplinary research drive by Pecan Street.

The one-line diagram of the Mueller community exhibits important facts about Mueller. The Mueller community only represents <5 % of the substation transformer capacity (1.55 / 35 MVA = 4.2 %). Therefore, impact to the utility should likely refer to the impact as seen from the service lateral service entrance to Mueller and not as seen from the transformer (T1) at substation 1.

The residential data recorded by Pecan Street confers elevated confidence in the simulation results. In contrast to developing computer models to mimic uncorrelated residential load and daily PV fluctuations consistent with the city of interest, using recorded data in one minute intervals together with a computer model that accepts this data reveals network-wide voltages, currents, and power flow profiles close to what is observed by the local utility.

It appears the distribution transformers at Mueller are sized to meet diverse EV charging levels in the evening hours. This remark is based on randomized charging levels (120 and 240 V), durations, and plug-in times. It is noted that this is an interim result and not general. Additional simulation studies (and for > 1 day) are recommended to assert whether or not EV charging will cause problems. In addition, merit is given to the utility for their foresight to deploying 50 kVA transformers at this community in anticipation of high concentrations of emerging technologies.

Most of the electrical footprint observed in this work stemmed from PVs rather than from EVs. This footprint was perceived as reversed power flows in transformers, diurnal voltage swells (> 240 V), poor power factor conditions through transformers and at the lateral, a reduction of current unbalance, reduced lateral power demand, a large number of PVs when compared to EVs, noticeable PV fluctuations at the individual home level, and from the uncontrollable scattering of PVs installed on phases $a$, $b$, $c$ which is out of the utility’s control. The aforementioned observations, as they continue to become impactful, will pose challenges to future control and protection schemes [39].

It should be noticed that the PV generation at Mueller does not leave the community. This generation is produced and consumed by residents not having PVs. Currently, the utility provides credit towards a residential customer’s bill for any power not consumed locally. While there is no profit in doing so, there is less distribution loss involved in buying and selling power closer to where it is needed rather than transmitting it over longer distances.
Bidirectional power flow in networks designed for flow in one direction (from source to load) improves distribution efficiency, provides voltage support, and reduces utility-side generation demand; however, it also introduces protection and control complexities not present before. Fault studies [16],[40] were not conducted, but are recommended for future work. For example, faults along substation feeders may be affected by PV in-feed current. Faults inside the community, along the distribution circuits, in lieu of such as high concentration of PVs, should be considered as well.

High penetrations of distributed generation at the consumer-end of electric network pose challenges to electrical infrastructures designed for radial power distribution. Renewable generation technologies (e.g., solar) are able to generate power at the received-end of the grid. This produces poor power factor conditions as seen in this work, and results in lower demands for active (billable) power. Moreover, the utility must schedule and provide reactive power although it does not bill for it.

The voltage profiles at the transformers are within acceptable levels under the conditions studied. This result suggests that residents are not affected by the high concentration of PVs and EVs at this community and at this time. These acceptable voltages are consistent with the transformer utilization and transformer %Z nameplate data [17],[28].

The visualization techniques presented in this work were somewhat new to electric power engineering. Among the important traits of these visuals is that the performance and uncorrelated behavior of all assets of a given type were seen using a single four-quadrant figure. Each quadrant view of the same data provided different insights into system behavior. This suggests that the view type alone helps reaching a broader range of conclusions. From the local utility’s perspective, computer simulations producing such bevy of views can be extremely valuable in determining situational awareness and discussed herein.

The change in transformer utilization was quantified with the model. This analysis makes it clear that the inclusion of PVs and EVs alter transformer utilization. The changes can be positive (increase), negative (decrease), or zero (no change). Although low levels of PV installation transformer throughput, at higher density, PVs also increases it and can result in higher transformer losses than without PVs. The second approach (right side of Fig. 5.9) to show change is using an after-to-before consumption ratio. It was shown that during some hours of the day, select transformers are used 300-400% more than before the incorporation of PV's and EV's. However, the changes are not sustained; they are present when PVs are fully illuminated and for those transformers that have more PV generation than residential load. This surplus caused power reversals through select transformers. The “heat map” approach to visualizing power changes also showed, by changing from light blue to yellow, that EVs can increase transformer utilization by 10 % during the evening hours, but is not as significant as the impact observed from PVs.

The lateral power demand significantly changed with inclusion of PVs and EVs. The most appreciable change was the reduction in real (active) power demand. After the inclusion of PVs, the power demand reduced from ~600 kW to ~200 kW, which is power no longer sold by the utility; instead, it is power produced locally by residents.

Local active (real) power generation results in poor power factor conditions experienced by the utility. It was shown that power factor can reduce to ~0.6. Nonetheless, reactive power demand is unchanged and its availability still the responsibility of the utility. That is, residences are
allowed to rely on the utility to provide reactive power, but the utility cannot bill for this service. This has, at least, two implications: first, residences cannot become grid-independent until they overcome this dependence; second, the utility must schedule generation to provide reactive power although residences do not pay for it.

The observed current unbalance produces voltage unbalances at the service terminals of different power apparatus—in particular, this may cause voltage unbalances for industrial customers outside Mueller. Comparing the current unbalance before and after the installation of residential PVs, it is seen that PVs re-balance the line currents downstream of the service entrance by decreasing the unbalanced demand. It is also possible un-even deployment of residential PVs (e.g., too many PVs in one phase) can result in pronounced unbalances elsewhere on the main feeder. But this effect was not studied here. It was noticed that phase b carries most of the residential load and also most PVs and EVs (Fig. 2.4).

Distribution losses were approximated in watts and in dollars. The dollar amounts are approximate. They are calculated by integrating power in one minute intervals and scaling the results by the billable price to residents. Although this is not how consumers are billed in practice, it is interesting to estimate, in this quick way, the potential dollar losses as a result of including PVs and EVs in a distribution system. As noticed from these results, PVs reduce diurnal cable losses as there is less current demanded from the utility. Although there are reduced losses, the change in monetary value is insignificant due to the low current values at the medium-voltage distribution levels such 12.47Y/7.2 kV; and also due to the assumed (and rounded) rate of $0.13/kWh. In the evening hours, EVs ramped cable losses upward between 6-10 PM, but this did not significantly change the monetary value.

The transformer conduction losses did not appear to change with the inclusion of PVs. This was because many PVs increase the losses while many other PVs decrease them. Comparing the before and after transformer losses, the aggregate dollar-result appears unchanged. The total cable and transformer losses, at the end of the day, also appeared to be the same. Interestingly, it appears that the reduction in losses due to PVs, and the increase in losses also due to PVs and EVs cancel out and results in a rather convenient “wash” for the utility. That is, high concentrations of emerging technologies (at the community level) may not alter existing distribution losses in either power or financially. They may also not warrant upgrading existing electrical infrastructure in modern communities as presented by this work. Additional data and analysis will be needed to determine if the results in this particular situation can be generalized.
References


