INTEGRATING AMI WITH GIS FOR ELECTRIC DISTRIBUTION TRANSFORMER LOAD MANAGEMENT

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Sue Ann Panton
Advisor: Pat Kennelly
Penn State University

Abstract

Electric utilities can use GIS to recoup a significant portion of the 20.7 billion dollars lost annually in the United States due to system inefficiencies. One example is through integration of Advanced Metering Infrastructure (AMI) data with GIS technology, which allows for targeted improvements to the distribution system. In an attempt to provide a cost-effective solution for integrating AMI with GIS, this pilot project utilized AMI winter and summer peak data to develop a custom application, which identifies undersized transformers. Through exploratory analysis, patterns revealed many instances of undersized transformers coincident with areas of short-term rentals suggesting a reduction in the ratio of services to transformer within these areas. Additionally, this study revealed a greater number of underground transformers are overloaded in comparison to overhead transformers. As more time is typically required to repair an outage caused by an underground transformer failure, the application helps to identify these potential threats to the electric system's reliability.

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SECTION 1. PROJECT BACKGROUND/INTRODUCTION

1.1 Project Background

Within the electric utility industry, choosing the correct sized transformer is vital to help reduce monetary losses in the distribution system. Oversized transformers have a cost associated with their operation, even with minimal or no load (Crowe, 2007); this equates to excess fuel costs to a utility when the unutilized capacities of the system's transformers are combined. If, for example a transformer is only loaded to 20%, it is not operating efficiently. While the inefficiency may be minimal, if the electric system is large, this small inefficiency may be multiplied by the number of instances throughout the system. In contrast, overloading an undersized transformer will cause excessive heating thereby reducing the useful life of the transformer or even cause failure. When a transformer fails, it will not only require replacement, but also contribute to the deterioration of the distribution system's reliability (Su et al., 2017).

Kissimmee Utility Authority (KUA), a municipality-owned electric utility provider located in Central Florida, has earned American Public Power Association's Reliable Public Power Provider (RP3) designation continually since 2007 (Kissimmee Utility Authority, 2018). The RP3 designation is awarded to public power utilities which demonstrate high proficiency in areas including reliability, safety, workforce development, and system improvement (American Public Power Association, 2020b). Within the electric utility industry, system reliability indices are also used as benchmarks for performance (American Public Power Association, 2020a).

Failures within an electric distribution system due to insufficient transformer sizing can be avoided by comparing the customers' actual use against the corresponding transformers' kVA (Kilovolt-Ampere) rating. Current methods available make this comparison cumbersome and/or cost prohibitive, thus one of the primary aims of this project is to identify undersized transformers within a distribution system to help produce actionable results and thereby potentially increase the electric system's reliability rating.

1.2 Description of the Problem

At Kissimmee Utility Authority (KUA), engineers determine transformer size in areas of single-family residence based on a combination of design standards that were created approximately 30 years ago and a developer's estimate of how much electricity may be used at any given time. These design standards were based on historical use data; since that time there have been trends which may potentially increase and/or decrease the actual amount of power consumed by a customer. Things like energy efficient appliances and LED lightbulbs can help to lower the amount of power consumed by a customer, while trends towards larger living spaces operate in contrast, potentially increasing the amount of power used by a customer (Crowe, 2007).

Currently, the only way our engineers know if a transformer is over- or under-loaded is through researching billing history within our Customer Information System (CIS). This approach requires a comparison of the average peak use of all customers being fed from the transformer in question to the transformer's kVA rating. With over twelve thousand single-phase transformer banks within our system, this is not an effective means of distribution transformer load management.

Recently KUA has moved toward smart-grid technologies by deploying Advanced Metering Infrastructure (AMI) to replace analog electricity meters within our system. At the time of this pilot project, 74% of KUA's meters had been upgraded; these smart meters have the ability to produce data at 15-minute intervals. One benefit of this technology is the ability for a utility to monitor and manage electric loads more efficiently and in some cases in near real time (Ashkezari et al., 2018). With an increased availability of data, the question arises - what level of analysis will prove to be the most beneficial for transformer load management.

1.3 Literature Review

A review of recent literature indicates advanced techniques are being utilized to incorporate AMI data with GIS. Nourjou & Hashemipour (2017) for example, utilized the Internet of Things and autonomous computer programs to connect outage sensor network and economic loss estimation services to produce a real-time Web Map Service. Guerrero-Prado et al. (2020) used big data and data analytics techniques to communicate trends and patterns with AMI data. Su et al. (2017) created a transformer load monitoring system which utilized smart meter data captured hourly to identify over- and under-utilized transformers. While working with big data can be beneficial, there are also drawbacks associated with these approaches. The monetary cost of working with big data may be prohibitive due to database sizing or network bandwidth limits. **Table 1** outlines technology limitations as stated within the literature when incorporating very large AMI data sets into a GIS.

Technology Limitations Stated in Literature	Work
Requires frequent data collection resulting in protocol errors and bandwidth constraints	Balakrishna & Swarup (2020)
Consolidation of big data was a time-consuming task	Guerrero-Prado, et al. (2020)
Cost of software and other components, requires investment in hardware and IT equipment	Ashkezari, et al. (2018)
Ineffective integrating of data visualization and detailed network topology for large-scale distribution system	Su, et al. (2017)
Big data challenge is efficiently managing data flows	Peppanen, et al. (2016)
Requires robust methods for managing big data and quality models	Peppanen, et al. (2015)
Large volumes of data lead to increased potential of data errors and confusion	Lo, Huang & Lu (2014)
Hardware and software limitations; storing and managing data	Triplett, Rinell & Foote (2010)

Table 1. Technologies and their limitations used to incorporate Advanced Metering Infrastructure (AMI) data within a GIS.

Triplett, Rinell, & Foote (2010) explored loss evaluation techniques within a test case distribution system via hourly load data collected over a five-day span. They concluded that while greater insight was obtained regarding system losses utilizing this method, this approach may not be practical or useful and instead suggested analyzing the system at differing states of interest from light loading to peak loading conditions (Triplett, Rinell & Foote, 2010).

1.4 Goals and Objectives

Based on the needs of KUA and findings from a review of recent literature, the goals of this study are:

(1) Utilize AMI peak data (winter and summer) to determine if distribution engineering design standards used for the placement of an appropriately sized transformer are still valid based on actual customer usage within areas of single-family residence. Using a snapshot of peak data should resolve the technology concerns found within the literature as these occurred when dealing with large volumes of data collected at frequent intervals.
   - If distribution engineering design standards require revision, collected data will play an integral role in their correction.

(2) Identify patterns through exploratory analysis which will further improve criteria used when placing an appropriately sized transformer in the future.
(3) Develop a custom application which will aid our engineers in identifying areas which may require electric reconstruction to avoid future power-related issues.

Through this study, I intend to provide an in-house, cost-effective solution to KUA so our organization can make more confident decisions based on sound data and actual patterns of use.

SECTION 2. METHODOLOGY

2.1 Data and Materials

The 2020 system winter and summer peak dates were identified using Open Systems International's Supervisory Control and Data Acquisition (SCADA) platform. These peak dates were used to obtain two targeted csv files produced by the Landis+Gyr Meter Data Management System containing winter and summer peak kilowatt (kW) readings from AMI meters. Additional data sets utilized for this analysis include:

- *Consumer* – KUA's feature class linked to CIS data containing customer information such as meter number, address, etc.
- *Transformer* – KUA's feature class containing transformer information such as: kVA sizing, phase, feeder ID, etc.
- *Transformer Unit Table* – KUA's table containing transformer unit information including year of installation, project number, etc.
- KUA's miscellaneous electric datasets of features participating in the Geometric Network, a method available in ArcMap for modeling networks:
    - *Primary Overhead*
    - *Primary Underground*
    - *Secondary Overhead*
    - *Secondary Underground*
    - *Service Points*
    - *Surface Structures*
- *Future Land Use* – Osceola County and The City of Kissimmee feature classes containing uses of areas
- *Parcels* – Osceola County Property Appraiser's feature class containing information for each parcel boundary

At the time of this analysis all data sources obtained were current.

The Service Points feature class participates in the Geometric Network; however, it lacks a unique field shared with the peak kW csv file. To circumvent this, two new fields "WPeak" (winter peak) and "SPeak" (summer peak) were created within the Consumer feature class and populated using temporary joins to the peak kW reading data from AMI meters. As Consumers are related to Service Points, the ArcGIS Attribute Assistant Copy Linked Record method was then used to populate the winter and summer peaks within the Service Points from the related Consumer (Figure 1). A Python script, explained in more detail in Section *2.2 Software and Technology*, was then used to populate the summed winter and summer peak values within a standalone table containing the Facility ID of the Transformer. That table was then used to populate the Transformer feature class.

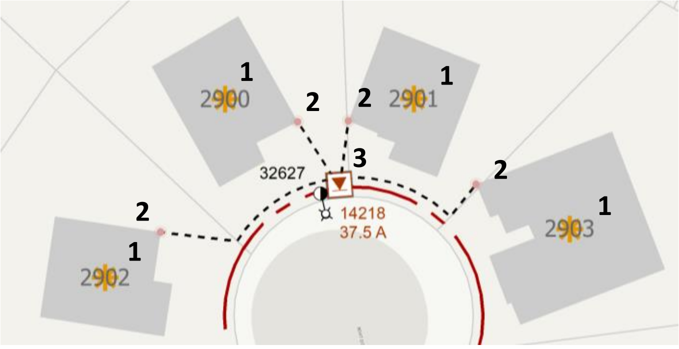


Figure 1. Consumers (**1**) are related to Service Points (**2**) within KUA's GIS; multiple Service Points (**2**) can be connected downstream from a single Transformer (**3**).

Future Land Use files obtained from Osceola County and the City of Kissimmee contained a total number of Land Use designations, 22 and 18, respectively. For organizational purposes and ease of analysis, seven Land Use categories were created and used to consolidate the 40 original Land Use designations:

- Conservation
- Commercial
- Institutional
- Mixed Use
- Residential
- Rural
- Other

Once the Transformer feature class was populated with the winter and summer peak values, data containing peak values was extracted. Within this Transformer subset, additional fields were added and populated for analysis including:

- Peak – the higher of the winter and summer percent peaks
- Winter Percent – winter peak percentage, calculated by dividing the winter peak by the rated kVA of the transformer and multiplying by 100
- Summer Percent - summer peak percentage, calculated by dividing the summer peak by the rated kVA of the transformer and multiplying by 100
- Peak Percent – the higher of the calculated Winter and Summer Percent
- Peak Range – the value range the Peak Percent lies within (ex. 80-100%, 101-125%, 126-150%, 151-272%)
- Substation – substation the transformer feeds from, populated by extracting the first two numbers of the Feeder ID
- Year – year the transformer was installed, populated using a join to the Transformer Unit table
- Land Use – land use designation for transformer location, populated using a spatial join

Undersized transformers were identified by comparison of their actual use during identified summer and winter system peaks against their rated kVA. Identified undersized transformers were organized into three categories (Table 2):

Undersized Transformer Categories	
151% - Over	Immediate Action
101% - 150%	Evaluate
80% - 100%	Monitor

Table 2. Criteria used to identify undersized transformers.

2.2 Software and Technology

Python 2.0 was utilized to populate the summarized winter and summer peak values within each transformer with the following steps:

- ArcPy's SearchCursor used to populate the transformer list with single phase transformers
- Transformer list looped through to:
    - Create a Feature Layer of the Transformer
    - Conduct a Geometric Network trace using ArcPy's Trace Geometric Network tool with the Transformer as the flag and disabling Primary Overhead and Primary Underground features from the trace to select all Service Points that are electrically fed from, or "downstream" of the selected Transformer
    - Copy the selected Service Points to a table
    - Calculate the sum of the Winter or Summer Peaks for the selected Service Points downstream from the selected Transformer
    - Search Cursor used to determine if a peak value was present for population
        - If a value was present, an Insert Cursor was used to populate the summed peak value within the table

The resulting table was then temporarily joined to the Transformer feature class to populate the Winter and Summer Peak fields.

A Feature Service of the Transformer feature class was published to ArcGIS Enterprise Portal using ArcMap 10.6.1. This service was utilized to create the 2020 Transformer Peak Dashboard (Figure 2).

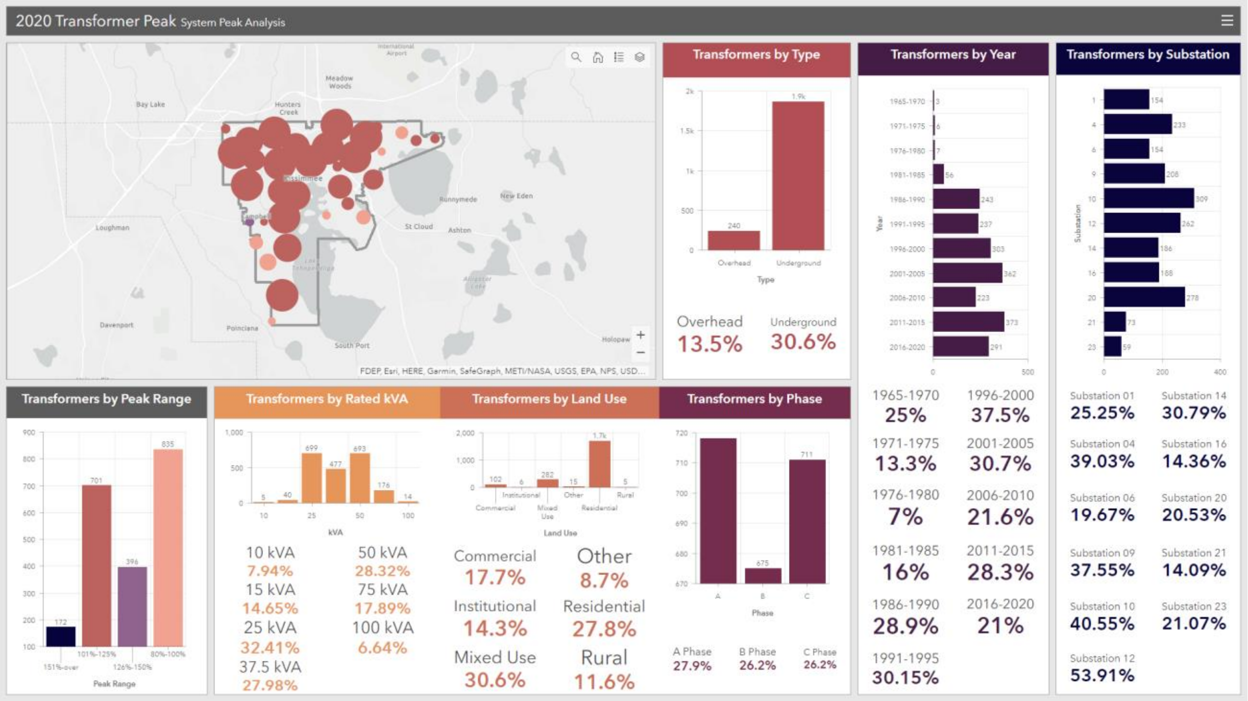


Figure 2. 2020 Transformer Peak Dashboard display.

2.4 Challenge and Limitations

A number of challenges and limitations arose during this pilot project. As KUA's GIS is versioned, difficulties were encountered when attempting to continually populate the transformer peak data using the Python code. To negate this, values were written to an external table, temporarily joined to the Transformer feature class, and Winter and Summer Peak fields populated. Due to the large amount of data that was processed for each downstream trace, a number of queries and iterations of running the script was implemented; multi-processing may be a method utilized to run the code more efficiently in the future.

The ArcGIS Attribute Assistant Copy Linked Record method has the ability to sum across different fields within the same feature. However, within our GIS, multiple Consumers are associated with Service Points via relationships. As a result, only Service Points related to a single Consumer were included in this study. In the future, this analysis can include Service Points related to multiple Consumers by utilizing a join, query, calculation, and data population .

Optimally in the future this will be a dynamic display, utilizing ArcGIS Arcade to calculate values on the fly. Additionally, a way for transformers to be excluded from the display once they are replaced in the field, making this an accurate representation of all oversized transformers at any given time.

SECTION 3. RESULTS AND DELIVERABLES

The created 2020 Transformer Peak Dashboard allows for interactive filtering of the display via differing combinations of selections within bar charts. These can be combined in any manner that is of interest to the user (Figure 3). This dashboard was used to facilitate exploration of the data for further investigation and analysis.

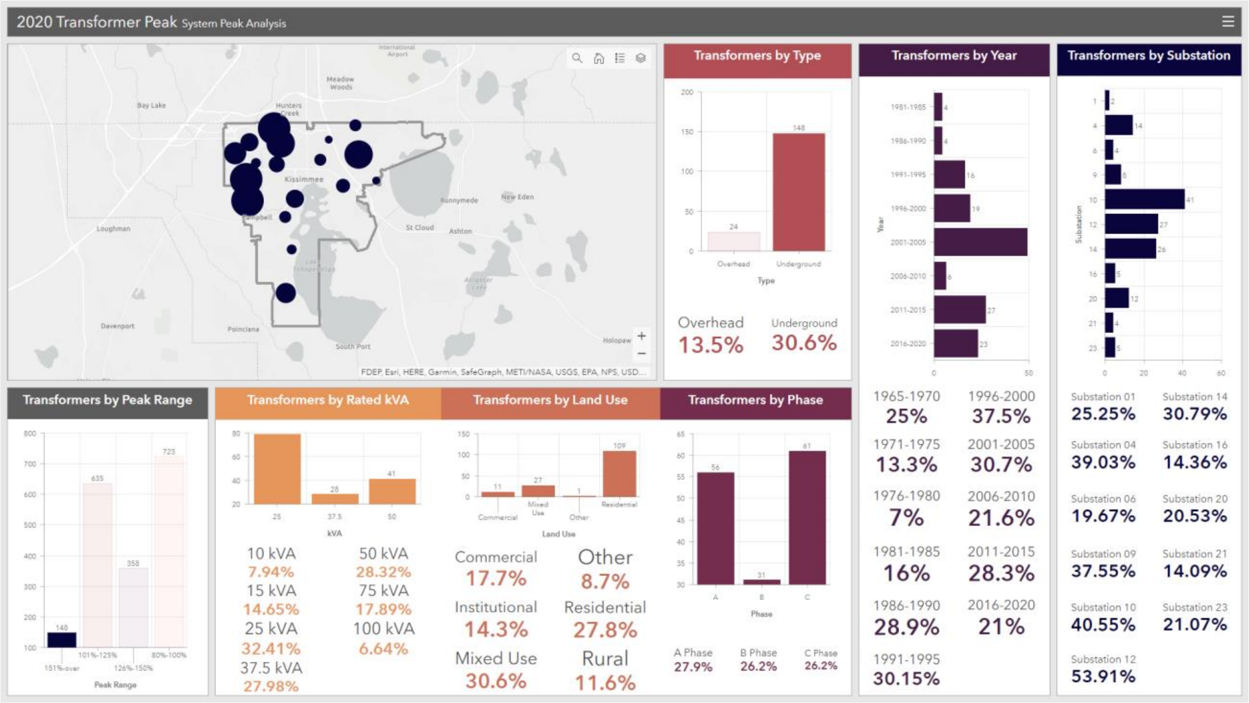


Figure 3. 2020 Transformer Peak Dashboard displaying all underground transformers loaded over 150%.

Statistical analysis of transformers was conducted on a number of categories: type, phase, substation, rated kVA, land use, and year of installation. 100% stacked bar charts were created to display the relative percentage of transformers over the 80% loading threshold in comparison to all transformers present within that grouping; they display a part-to-whole relationship (Appendix *A1*).

By phase this analysis revealed a relatively equal distribution of transformers loaded over 80% (Figure 4 within Appendix *A1*). By land use it appears areas of Mixed Used designation are loaded at a higher rate than residential areas (Figure 5 within Appendix *A1*). It is worth noting however; according to Osceola County's Comprehensive Plan (2021) a Mixed Use designation includes areas of residence, shops, schools, workplaces, parks, etc. It is therefore difficult to determine the actual distribution of undersized transformers by land use category using this method.

Focusing on transformers loaded over 150%, a number of findings presented themselves. The concentration of transformers loaded over 150% are in the northwestern portion of the territory. It was hypothesized these areas were coincident with areas of short-term rentals, properties which are rented for short periods of time. As these areas are restricted to specific boundaries within Osceola County, the Short-Term Rental Overlay boundary was obtained. Upon overlaying areas of transformers loaded over 150% and the Short-Term Rental overlay (Figure 6), these suspicions were confirmed. This may be due to the mentality of short-term tenants, who are charged the same amount, regardless of how much power is used at the residence, paired with the relatively hot conditions of Central Florida. The initial observation of a high percentage (53.9%) of transformers loaded over the 80% threshold originating from Substation 12 led to this discovery (Figure 7 within Appendix *A1*).

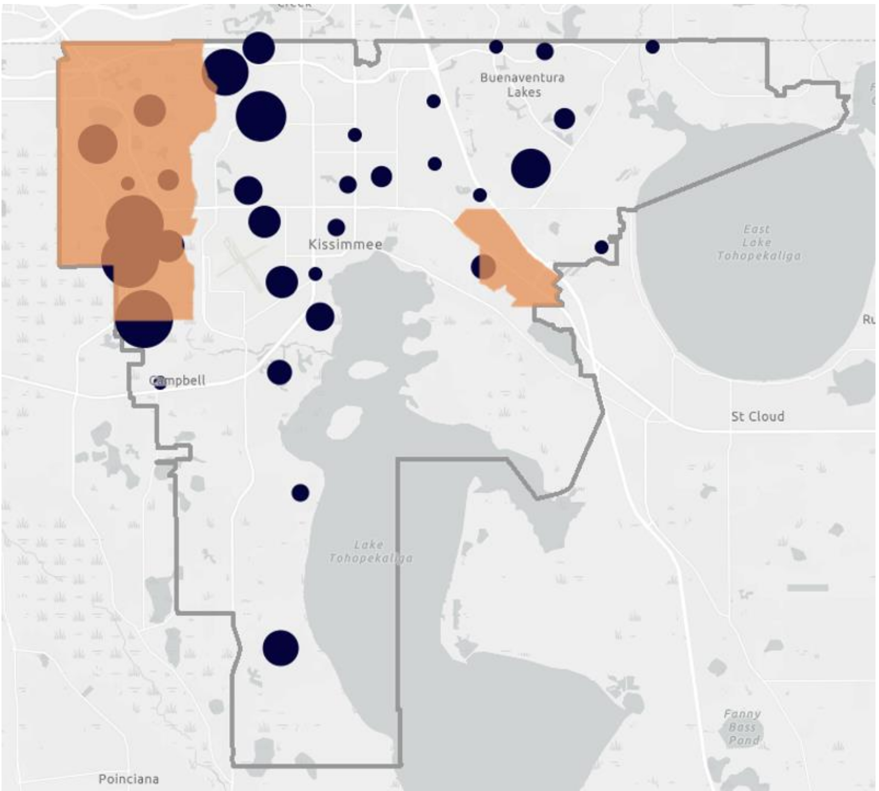


Figure 6. All 2020 transformers loaded over 150% shown with the Short Term Rental Overlay.

An additional finding helped to confirm suspicions that underground transformers are overloaded at a greater rate than overhead transformers (Figure 8 within Appendix *A1*). Focusing on transformers by type, either overhead or underground, we found there were 24 overhead transformers loaded over the 150% threshold in comparison to 148 underground transformers (Figure 9). This finding is of particular interest to KUA's reliability rating. The longer the duration of an unplanned outage, the greater the negative impact on the utility's rating. As it typically takes longer to restore power caused by an outage on an underground transformer in comparison to an overhead transformer, this dashboard aids in creating a hierarchy of priorities in terms of which overloaded transformers to address first.

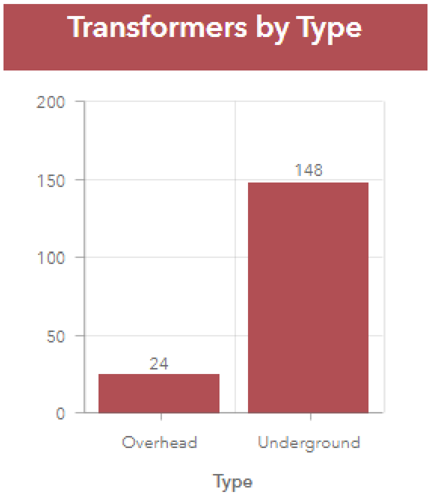


Figure 9. Transformers loaded over 150% threshold by type.

Regarding age of infrastructure, transformers installed between 2001 and 2005 seemed to be outliers. Over 13% of those transformers were overloaded and 4.3% were over the 150% overloading threshold; this is much more than any other time frame (Figure 10). These occurrences may or may not be linked to individual engineer's methods of transformer placement. Future iterations of this analysis can include information regarding the individual that designed the electric infrastructure within the area by utilizing the CreationUser field. This will help determine if these occurrences were in fact linked to a particular individual.

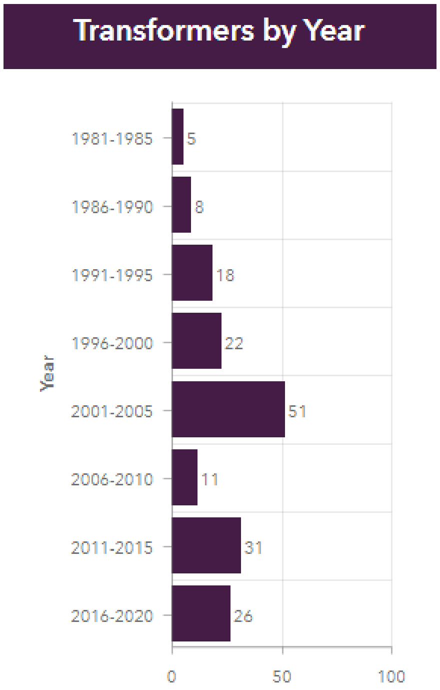


Figure 10. Transformers loaded over 150% threshold by year of installation.

Lastly, it was noted 25kVA transformers were grossly overloaded in comparison to 37.5 kVA transformers, at a rate of three-to-one; and 50 kVA transformers, at a rate of two-to-one (Figure 11). When further exploring 25 kVA transformers over the 150% threshold it was discovered although many of them were feeding four houses, there were some feeding up to seven (Figure 12). As a result, some engineers have adjusted their design standards to connect only three residents to a single 25 kVA transformer to avoid overloading.

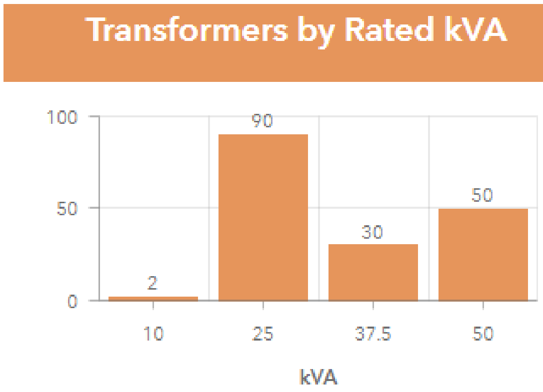
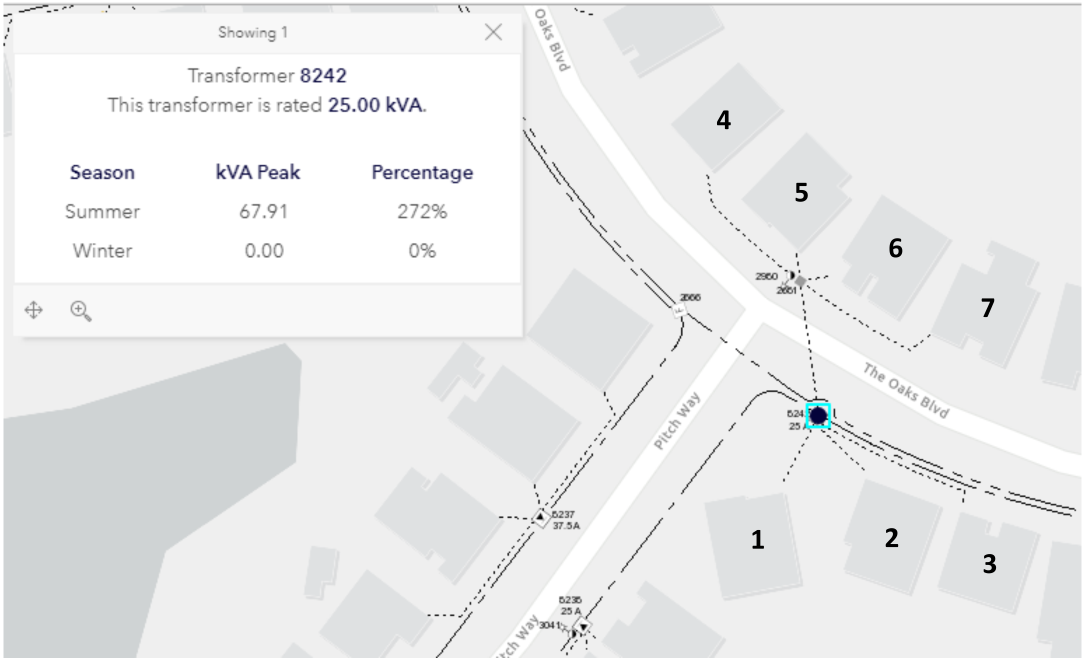


Figure 11. Transformers loaded over 150% threshold by rated kVA.


Showing 1

Transformer 8242
This transformer is rated 25.00 kVA.

Season	kVA Peak	Percentage
Summer	67.91	272%
Winter	0.00	0%

Figure 12. 25kVA underground transformer feeding seven houses.

SECTION 4. SUMMARY

This study presents one approach for integrating AMI with GIS to facilitate transformer load evaluation within a distribution system. A pilot project conducted on a portion of Kissimmee Utility Authority's territory was used to determine the viability of this proposed method. The first of three objectives was to determine if engineering design standards used to place an appropriately sized transformer within areas of single-family residence were still valid based on actual patterns of use. Current standards dictate a 25 kVA transformer feed 2 to 3 - 200 AMP service single family homes (Figure 13), however preliminary observations revealed instances of four to seven houses connected to a single underground 25 kVA transformer (Figure 12) and ten houses connected to a single overhead transformer of the same size (Figure 14). Some flexibility is available when determining appropriate transformer sizing with factors such as the size of the service, the presence or absence of energy efficient appliances, the size of the residence, etc. all playing a role. It was theorized many of the observed instances of four or more homes connected to a 25 kVA underground transformer were simply due to an initial oversight.

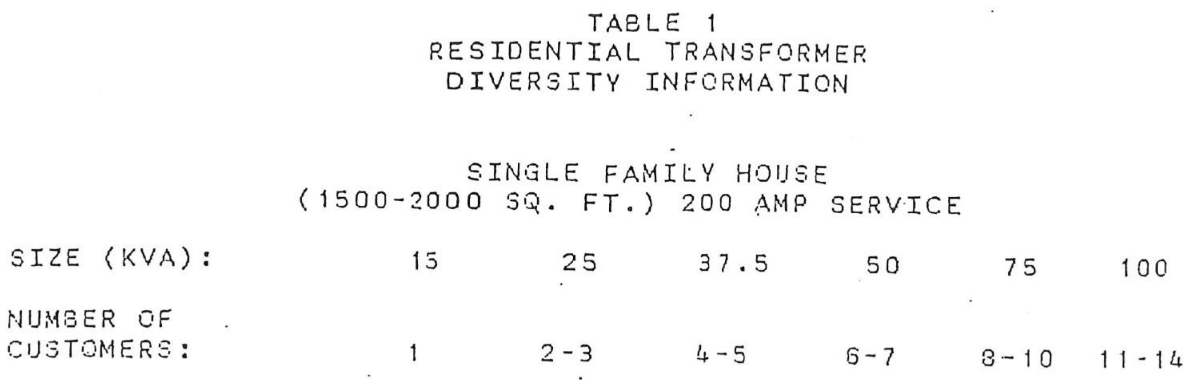
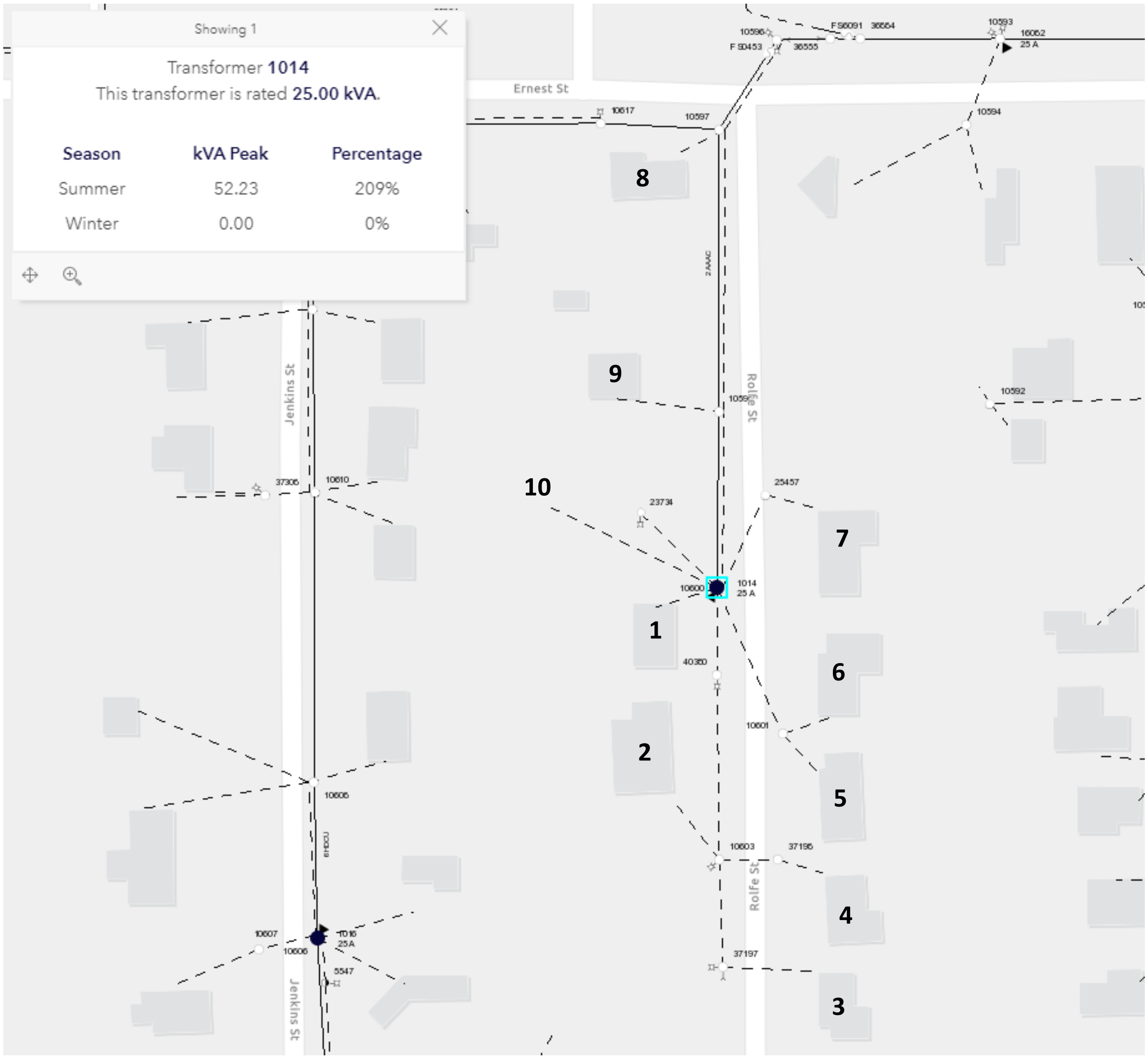


TABLE 1
RESIDENTIAL TRANSFORMER
DIVERSITY INFORMATION

SINGLE FAMILY HOUSE
(1500-2000 SQ. FT.) 200 AMP SERVICE

SIZE (KVA):	15	25	37.5	50	75	100
NUMBER OF CUSTOMERS:	1	2-3	4-5	6-7	8-10	11-14

Figure 13. Distribution engineering design standards used for the placement of an appropriately sized transformer.


Showing 1

Transformer **1014**

This transformer is rated **25.00 kVA**.

Season	kVA Peak	Percentage
Summer	52.23	209%
Winter	0.00	0%

Figure 14. 25kVA overhead transformer feeding ten houses.

In the case of undersized overhead transformers (Figure 14), previously the general practice was to connect additional service(s) to an existing transformer rather than upgrading the transformer to an appropriate larger size. Therefore, while initially these overhead areas may have been designed appropriately, future additions likely contributed to their overloading.

The second objective of this study was to identify potential patterns which may further improve criteria when placing an appropriately sized transformer in the future. Spatial analysis was conducted on any transformer loaded over the 80% threshold; those findings are summarized using 100% stacked bar charts within Appendix *A1*. Additional further analysis was conducted on transformers loaded over 150%.

Many transformers loaded over 150% were coincident with areas of short-term rental properties, suggesting a connection between increased energy use and short-term rental locations. Underground transformers are overloaded at a greater rate than overhead transformers. As it typically takes longer to restore power caused by an outage on an underground transformer in comparison to an overhead transformer, the identification of undersized underground transformers is of particular importance when wanting to address potential sources of threat to KUA's reliability rating.

The final objective was to develop an application that identified areas that may require electric reconstruction to avoid future power-related issues and/or transformer failures; this was accomplished with the creation of the 2020 Transformer Peak Dashboard.

This pilot project proposed an in-house, cost-effective solution for integrating AMI with GIS for electric distribution transformer load management. The presented solution can be further improved as discussed in *Section 2.4 Challenge and Limitations* to broaden the scope of this analysis to include Service Points related to multiple Consumers.

Through spatial and statistical analysis, this project revealed valuable information regarding undersized transformers within our territory. With this knowledge our engineers can now make more informed decisions and necessary updates to the electric system to help reduce system failures due to insufficient transformer sizing. Moving forward the intent is to conduct this analysis annually to make additional improvements to the system that will help to further increase KUA's reliability.

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APPENDIX

A1. 100% Stacked Bar Charts by Subject

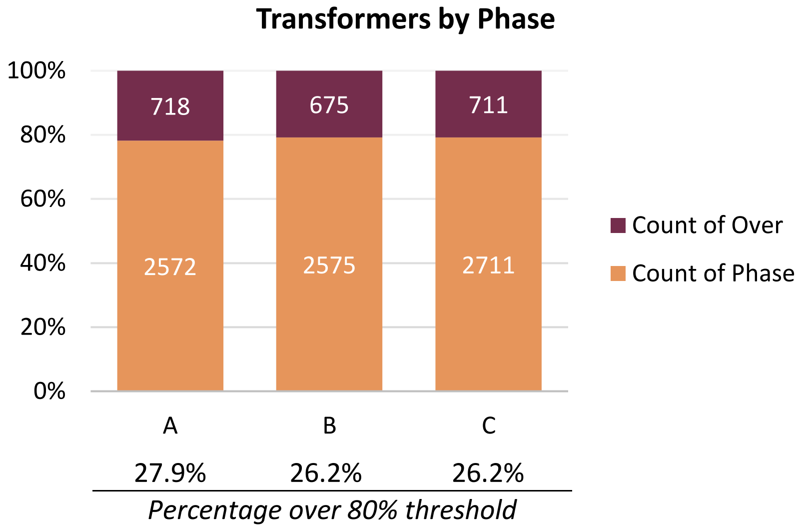

Figure 4. 100% stacked bar chart of transformers by phase.

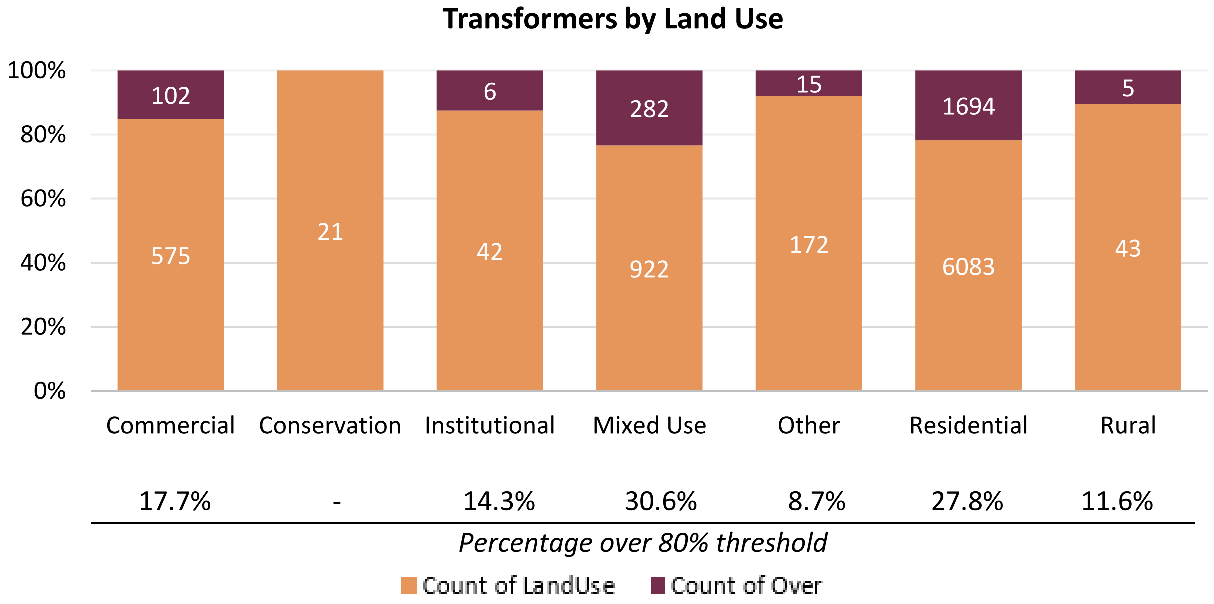

Figure 5. 100% stacked bar chart of transformers by land use.

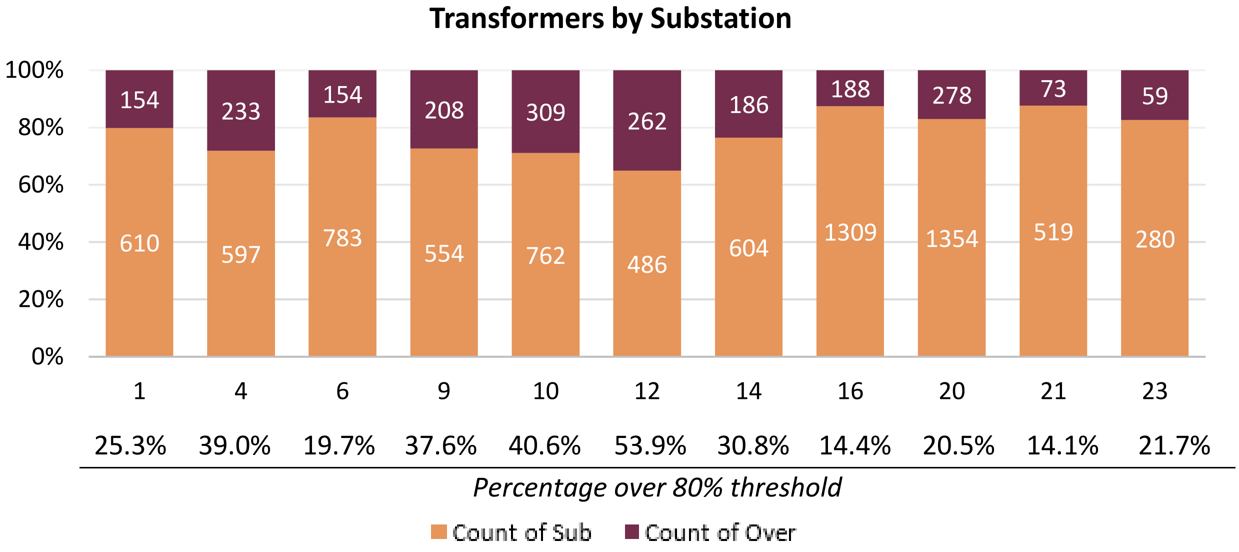

Figure 7. 100% stacked bar chart of transformers by Substation.

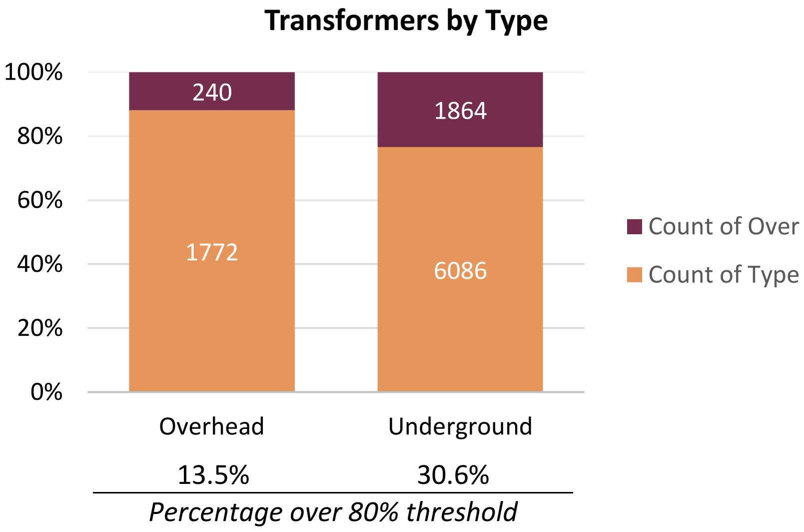

Figure 8. 100% stacked bar chart of transformers by type.