Improving Power Distribution System Situational Awareness Using Visual Analytics

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***Abstract*—Traditionally, distribution system operators had limited visibility beyond distribution system substations. It was not unusual for electric utilities to have insufficient information about the network and phase connectivity model for the distribution system. This resulted in limited situational awareness at the distribution system level. In this paper, a visual analytics approach to gleaning intelligence from the vast amounts of data accumulated in the distribution system is proposed. The web-based visual analytics interface integrates data from heterogeneous datasets such as AMI, GIS and SCADA. The interface is designed to enable distribution system operators visualize and analyze the state of the distribution system over time. This paper presents the use of the visual analytics system to identify mismatched meter-to-transformer associations and to visualize voltage violations in a real-world distribution network.**

***Index Terms*—advanced metering infrastructure (AMI), big data, data mining, data visualization, situational awareness, supervisory control and data acquisition (SCADA), visual analytics**

I. Introduction

The 2003 Northeast blackout was, among other reasons, attributed to limited situational awareness, inadequate power grid visualization and failing to act on the loss of key transmission lines due to insufficient information about the state of the grid [1], [2]. To improve situational awareness, utilities deployed phasor measurement units, sensors, and two-way communication devices, thus increasing monitoring and control of the power grid. Consequently, this led to data explosion, necessitating better visualization techniques for these large data.

Visualization provides a way to intuitively demonstrate and quickly utilize the key information extracted from big database. When presented in visualization interface, data can be leveraged to inspire and change the way people see the world around them. Situational awareness can provide monetary improvements through increased reliability, visualization and detection of problem areas, such as overloaded lines and voltage above and below standard limits at the point of common coupling. It also increases stakeholder engagement by displaying complex information in a more appealing and understandable manner that users are typically familiar with from applications such as Google maps [3].

Several studies aimed at improving power grid visualization have been conducted. Klump et al. [4], for example, presented an advanced visualization application that enable grid operators monitor grid conditions in real-time. Some visualization techniques employed in their work include maps, graphical alarms, power flow animation and contouring. Similarly, other studies have developed power grid visualization tools for contingency analysis [5], [6].

A 3D graphical user interface was presented for advanced visualization of the system state and events by Peppanen et al. [3] utilizing AMI and SCADA data for the Georgia Tech distribution system. The GUI provides real-time and historical visualization from the metering database and also shows AMI and simulation results, power flow direction and magnitudes along the power lines.

However, most of these studies do not incorporate data analytics into the visualization applications. Following this, a group of researchers at Pacific Northwest National Laboratory (PNNL) developed a visualization system prototype, GreenGrid, to enable grid operators identify vulnerabilities of the power grid and, thus prevent wide-area grid disturbances [7]. The functionalities of GreenGrid were demonstrated using data collected moments before the Western North America Blackout in August 1996. This work was extended to Wong et al.'s [5] power grid contingency analysis. A similar visualization tool, GridOPTICS, was developed through PNNL's Future Grid Power Initiative to improve power grid situational awareness. GridOPTICS tools provide visualization and decision-making support for power system operators by converting large amounts of data into actionable intelligence [8], [9].

It is important to note that these studies focus on visual analytics for the transmission system, but not at the distribution system level. Prior to the installation of smart meters at customers' premises, electric utilities had limited visibility at the distribution system level [10]. The installation of smart meters contributed not only to the improvement of energy billing, but also to the situational awareness of the distribution system beyond distribution substations. Nonetheless, the deployment of smart meters, two-way communication systems, intelligent devices and sensors at the distribution level has also led to the accumulation of big data.

To this aim, this paper proposes a visual analytics approach which leverages massive distribution system data to improve situational awareness of the distribution system. Visual Analyt-

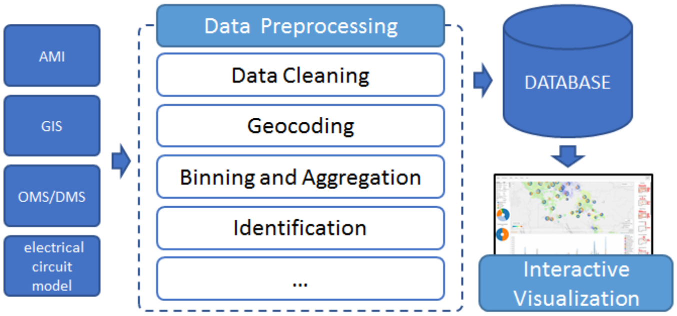

Fig. 1: System pipeline for the visual analytics system.

ics is a highly interdisciplinary field of research that integrates interactive visualization, and automated data analysis methods to address very complex real-world problems [11], [12]. Rather than displaying large distribution system data in tabular formats, visual analytics allows distribution system operators to monitor, analyze and visualize the status of the system in a more interactive manner [13], [14].

The paper is organized as follows: Section II describes the application of visual analytics in power systems and the web-based visual analytics interface developed. Section III presents the data sources utilized in this study. Section IV discusses the results achieved from the visual analytics interface. Section V concludes this paper and proposes ideas for future research.

II. Visual Analytics System for Electric Power Distribution Systems

This paper presents a prototype of a web-based visual analytics system that enables distribution system operators to analyze distribution system data collected from various sources such as advanced metering infrastructure (AMI), geographic information system (GIS), outage and distribution management systems (OMS/DMS), and electrical circuit models. These data collected over time contain various meter alarms and system events such as service voltage, power failure, power restoration, etc. The interface permits the user to identify spatial, temporal and categorical patterns of events and meter alarms by highly coordinated visualizations with multiple automated analysis algorithms. Through the visualizations, the user makes sense of the events in space and time, and identifies relationships between events. This paper presents applications of the visual analytics interface to a real-world distribution network.

A. Data and Preprocessing

The AMI dataset consists of measurements (voltage, current, frequency, and phase angle), alarms (such as power failure and power restoration), and energy usage data from metering devices. The GIS dataset includes geospatial information about the distribution network and its components. The SCADA dataset consists of event-driven data about distribution system devices such as transformers, reclosers, and breakers. It also includes substation and feeder information and measurements, as well as logs of alarms and events triggered by devices or manually entered into the system. The OMS/DMS dataset includes information on network devices, their ratings, locations, and normal states. This dataset also provides records of outages in the system, either reported by customers or field crew, and other information relevant to fault location and service restoration.

Fig. 1 shows the pipeline for the system. First, the data is cleaned to remove all unnecessary attributes and irrelevant parts. For the GIS data, the latitude and longitude coordinates are assigned to the GIS components, and connections are made between different components (e.g., connections between meters and transformers) and other data sources. In addition, a feeder circuit diagram is exported from CYME, and assigned a proper georeference. The AMI and OMS/DMS data to be used in different visualizations are also binned and aggregated. The preprocessed data is stored in a database server and used for the visual analytics interface.

B. Visual Analytics Interface

Fig. 2 illustrates the visual analytics interface. This interface comprises four main views: (A) Map View, (B) Alarm Timeline View, (C) Calendar View, and (D) Map Control Menu. The interface is developed using open source web libraries such as D3 [15] and Leaflet [16].

The map view (Fig. 2A) shows GIS data (such as transformers, meters, and switches) on a map. In addition, this view has multiple layers that illustrate several functionalities used to identify features and relationships between the GIS components and the distribution network data. The alarm timeline view (Fig. 2B) shows temporal behaviors of meter alarm events. It enables quick identification of frequencies and patterns of the alarm events over time. When the user selects a time range in the view, the map view is updated accordingly. The view uses the same color assignment for the alarm events as in the cluster map layer so that the user quickly makes connection between different features. The calendar view (Fig. 2C) shows daily, weekly, and monthly distributions of the meter alarm events. It allows the user to quickly identify days of particularly high numbers of alarm events within a month. The map control menu (Fig. 2D) provides the control switches to switch over basemaps (topographic, streets, satellite view and so on), different map layers (heatmap, event cluster, circuit view and etc.), different types of measured voltage (maximum, minimum and average), overhead and underground primary and secondary circuit views. There is also an option to show the mislinked transformers based on the distance between the service transformer and the customer meter.

In addition to the above views, the interface includes a data table (Fig. 3). The user can open the table view that displays raw data from a selected time range. This view also shows a daily distribution of alarm events, and voltage profile of a selected meter over a month as bar charts, transformers information and service quality data of each meter including 3-phase voltage measurements.

Fig. 4 displays the various map layers on the interface map view. The heatmap and cluster layers (Fig. 4A and B) represent

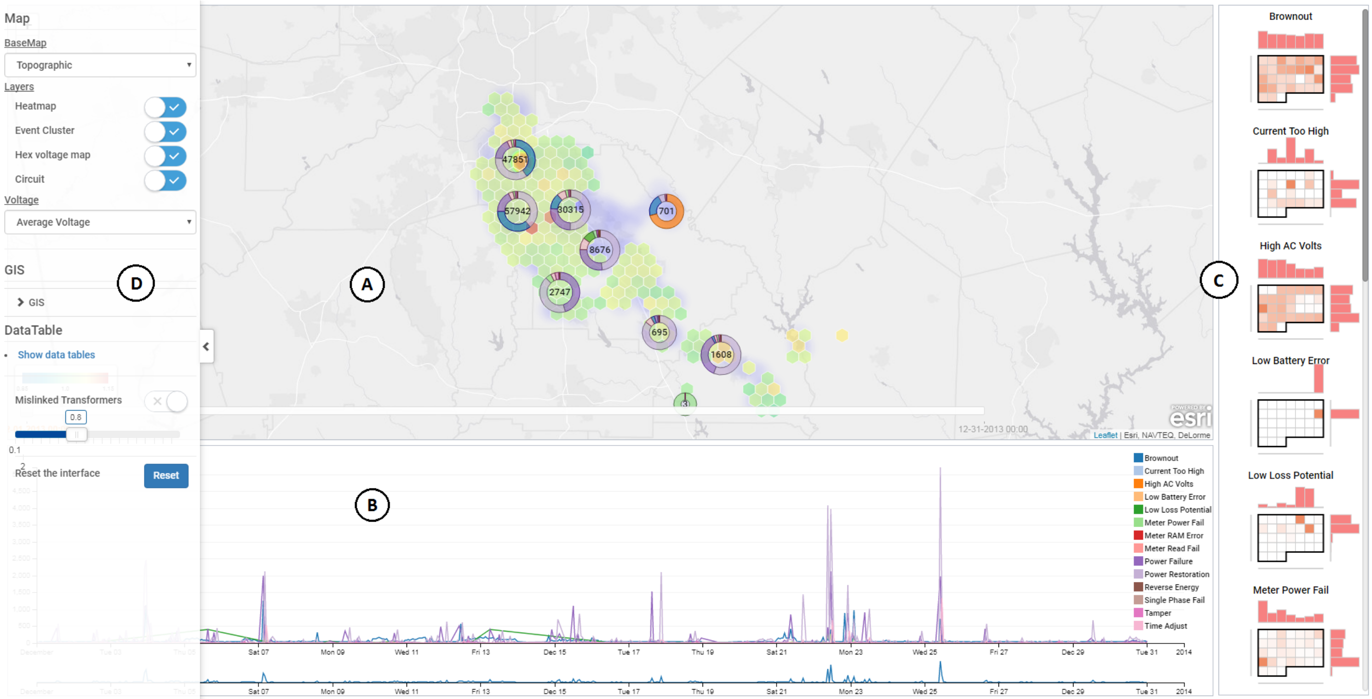

Fig. 2: Visual Analytics Interface: the interface comprises 4 main views. A) Map View, B) Timeline view, C) Event Calendar View and D) Map Control Menu.

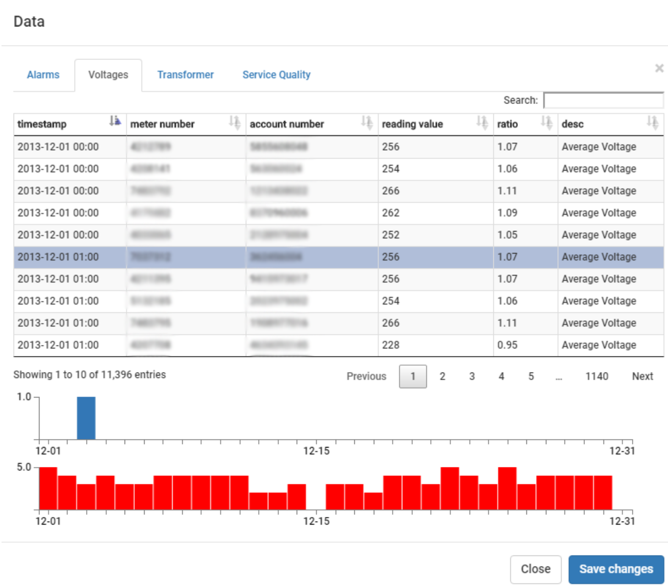

Fig. 3: Data table showing meter alarms, voltages, transformer and service quality data

frequencies of meter alarm events so that the user can quickly identify areas where alarm events are most concentrated. The cluster layer aggregates the alarm events based on the current zoom level and displays them as rings. The numbers centered in each ring represent the number of all alarm events in that area. Ring segments indicate different alarm events. The hexagonal heatmap (Fig. 4C) represents the voltage readings across the distributed feeder. Colors are assigned to each cell based on average voltage reading (in per unit) of the meters within the cell. Dark blue indicates undervoltage, red indicates overvoltage, and green indicates acceptable voltage as defined by the ANSI C84.1-2016 standard [17]. The user can change the type of the voltage profiles (average, maximum or minimum) from the Map Control Menu. In addition, the user can change the timestamp of the voltage profiles using the slider at the bottom of the menu. The map view also shows a feeder circuit diagram as a map layer (Fig. 4D) that enables the user to view the circuit schematic with the other map layers including several basemaps (road, street, satellite etc). The four views are highly interactive and coordinated with one another. This enables the user to explore and discover hidden features of the data from different views of the interface.

From the Map Control Menu (Fig. 2D) in the GIS section, one may select to view different overhead and underground distribution system circuits including primary and secondary. For instance, Fig. 5 shows an overhead secondary circuit has been selected in the map view and, it displays the connectivity of the service transformers (green circles) and the meters in this circuit based on the GIS data. It is also worth mentioning that the transformers represented by green circles are those whose customer meters are connected within a reasonable distance, while transformers with mislinked meters are represented by yellow circles.

C. Application of the Interface for Improved Situational Awareness

The visual analytics interface described herein provides opportunities to improve situational awareness by uncovering insights from distribution systems data. Some possible ap-

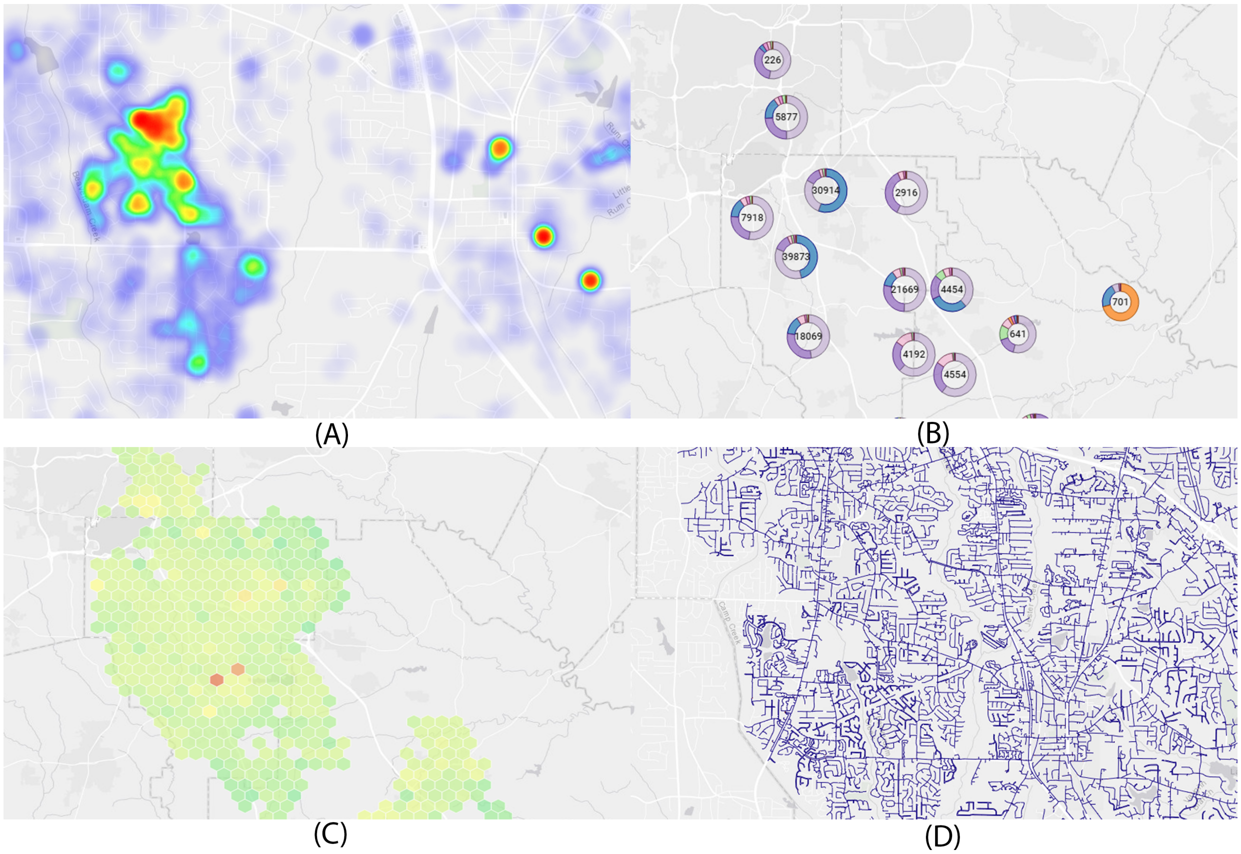

Fig. 4: Map layers: (A) heatmap, (B) marker cluster, (C) hexagonal heatmap, and (D) feeder circuit diagram. The user can toggle each layer on and off.

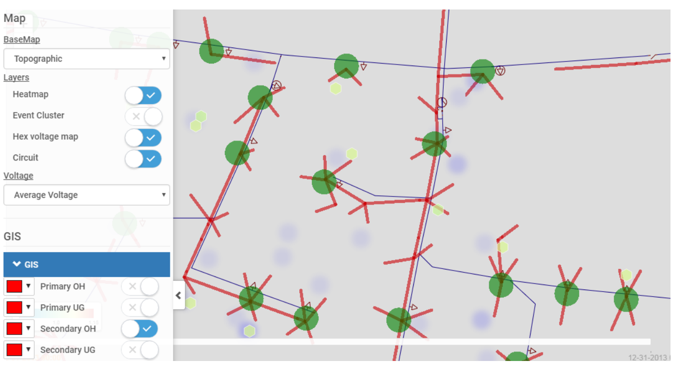

Fig. 5: Distribution system secondary circuit view based on GIS data

plications of this interface include asset management, outage awareness, and grid optimization.

For example, using event-driven data collected over time from SCADA, AMI and GIS, the visual interface could create a playback of sequence of events leading up to an outage. This playback feature could assist system engineers and operators in analyzing complex outages, and also reduce fault location times. On the other hand, predictive health indices could be developed for different distribution system devices such as transformers and protection devices by leveraging different datasets. This enables system operators to visualize devices on the verge of failure, thus allowing for the replacement of these devices even before they fail. Also, the visual interface can verify phase and network connectivity models for a distribution network. Using GIS data and voltage measurements from smart meters, the phase IDs of transformers, meters and other single-phase devices can be validated.

These use cases can be resolved by applying pattern recognition and correlation algorithms embedded in the visual analytics interface to different distribution system datasets. In this paper, the visual analytics interface reveals inaccurate meter-to-transformer associations, and voltage violations that exist within a distribution network.

It is worth mentioning that the visual analytics interface leverages data from heterogeneous datasets. Typically, electrical utilities manage distribution system data by using proprietary systems developed by different vendors, thus hampering data integration across these different systems. However, this visualization tool integrates data from different datasets (e.g. AMI, SCADA, GIS, OMS/DMS) allowing for more robust decision-making and improved data accuracy.

III. Case Studies

The distribution system data used in this work is obtained from an electric utility via EPRI's Distribution Modernization Demonstration (DMD) Data Mining Initiative (DMI) [18]. The data includes GIS, AMI, SCADA, OMS/DMS, and electrical circuit data from a real-world distribution network consisting of over 100 feeders serving more than 150,000 customers within a 600-square mile area. The network comprises threephase and single-phase sections of overhead lines and underground cables.

A. *Visualization of Voltage Violations*

As system conditions change throughout the day due to changes in loading or fault conditions, system voltages are bound to change accordingly. To maintain voltages within the required limits, it is necessary for distribution system operators to have knowledge of voltages at different nodes across the distribution network.

Using voltage measurements from the AMI dataset, and geospatial information from the GIS dataset, the interface provides a visual representation of voltages in the network over time using the hexagonal heatmap. The interface also reveals voltage violations in the system. By hovering over the heatmap, the voltages of the meters in a particular area are displayed. The voltage information provided could reveal opportunities for voltage optimization programs in the distribution network.

B. *Mislinked meters*

An application of the tool is the prompt visualization of meter-transformer connections. When a meter is selected, the connection to the transformer (and the other meters connected to that transformer) is quickly made. Similarly, when a transformer is selected, the connection between all the meters connected to that transformer is promptly made (Fig. 6). This capability highlights whether meters connected to the same transformer experience the same alarms, and is relevant to accurate phase identification for transformers and meters.

In the past, utilities resorted to paper maps to correctly identify phase connectivity for customers or single-phase taps. In other cases, repair crews had to be dispatched to the field to verify the transformer feeding a group of customers. This is particularly tedious with underground systems. Information on phase identification could be lost when new customers are added to the distribution system, during restoration efforts after widespread outages (especially weather-related outages) or through errors when transferring device or network connectivity data into the DMS or GIS system. Accurate phase connectivity models are important for efficient planning and operation of the distribution system, particularly in limiting the level of system unbalance.

The visualization interface also allows the user to easily identify mislinked meters (customers), by displaying them on the map with connected lines as shown in Fig. 7. The two meters displayed are supposedly connected to the same transformer, but located further than 0.1 mile (161m) apart. This is inaccurate, and could be attributed to inaccurate transformer identification numbers contained in the AMI and GIS datasets.

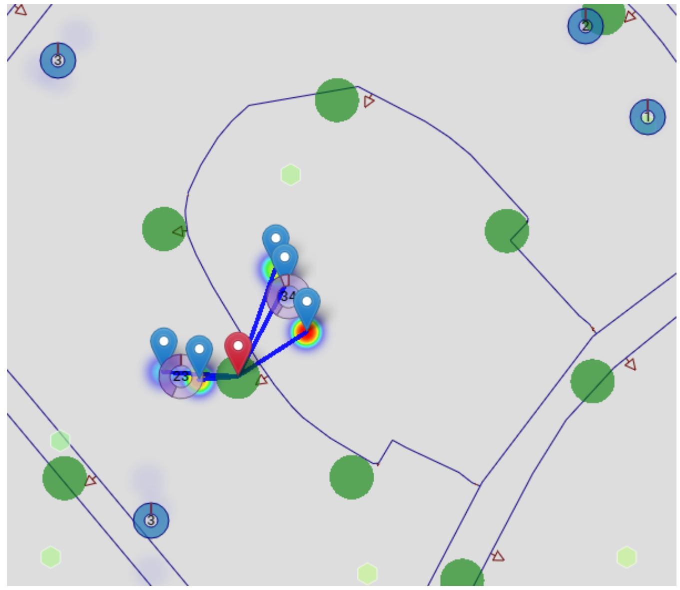

Fig. 6: Example view of a meter-transformer connection. The selected transformer has five meters. The summary view shows the information of the selected transformer and summary of the alarm events of the meters.

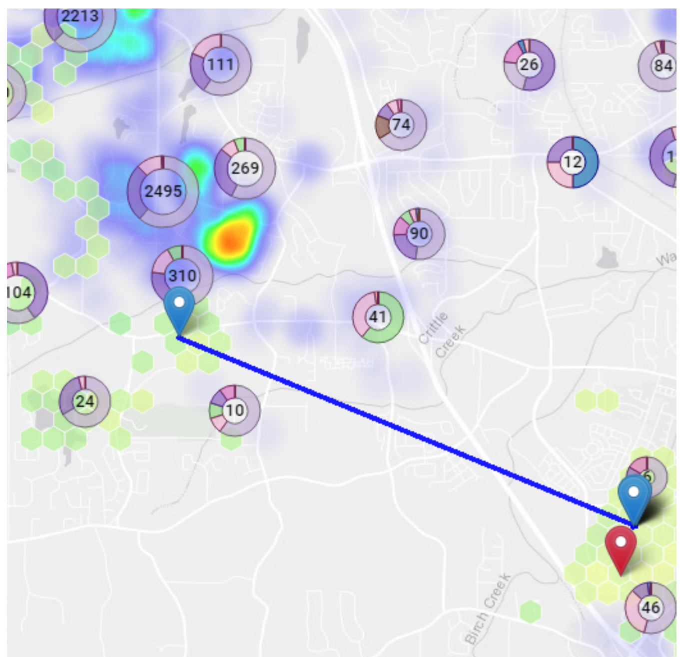

Fig. 7: Example of mislinked meters.

IV. Conclusion

In this paper, a visual analytics interface that improves the situational awareness of the electric power distribution system was presented. The interface integrates data from various datasets including AMI, GIS, SCADA and OMS from a real-world distribution network. Two use cases were presented to demonstrate the use of the interface to identify meters with out-of-range voltage measurements and mislinked meters and transformers.

Use cases requiring more advanced analytics (such as outage playback, or analyzing momentaries and voltage sags) would require data as close to real-time as possible since system conditions could change severally within a 1-second time frame.

Future work will incorporate additional heterogeneous datasets such as weather and social media data. The visual analytics systems will also be used for outage replay and prediction scenarios using real-time data.

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