Electrical Distribution Modeling:
An Integration of Engineering Analysis and Geographic Information Systems

by
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Abstract

This thesis demonstrates the value of integrating electrical distribution engineering analysis with Geographic Information Systems (GIS). The 37-Node IEEE Feeder model was used as the base distribution system in this study. It was modeled separately, both in software capable of unbalanced load-flow and in an industry-standard GIS environment. Both tools utilized were commercially available, off-the shelf products indicative of those used in academia and in basic GIS installations. The foundational data necessary to build these models is representative of information required by a variety of utility departments for a multitude of applications. It is inherent to most systems within an enterprise-level, business-wide data model and therefore can be used to support a variety of applications. In this instance, infrastructure information is assumed to be managed and housed with the GIS. This data provides the required information as input for load-flow calculations. The engineering analysis is performed within DistributionSystem 4.01 and its output is passed back to the GIS in tabular format for incorporation. This thesis investigates the transfer of information between GIS and DistributionSystem 4.01 and demonstrates the extended display capabilities in the GIS environment. This research is implemented on a small scale, but is intended to highlight the need for standardization and automatic integration of these systems as well as others that are fundamental to the effective management of electrical distribution systems.
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<td>Geographic Information System</td>
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<td>CIM</td>
<td>Common Information Model</td>
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<td>ESRI</td>
<td>Environmental Systems Research Institute</td>
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<tr>
<td>COTS</td>
<td>Commercial, off-the-shelf</td>
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<td>GPS</td>
<td>Global Positioning Systems</td>
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<td>IEC</td>
<td>International Electrotechnical Commission</td>
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<td>SIDM</td>
<td>Systems Integration for Distribution Management</td>
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<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
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<td>SDSFIE</td>
<td>Spatial Data Standard for Facilities, Infrastructure, and the Environment</td>
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<td>FMSFIE</td>
<td>Facilities Management Standard for Facilities, Infrastructure, and the Environment</td>
</tr>
<tr>
<td>AM/FM</td>
<td>Automated Mapping/ Facilities Management</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
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<tr>
<td>CCAPI</td>
<td>Control Center Application Program Interface</td>
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<td>DMS</td>
<td>Distribution Management System</td>
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Chapter 1 - Introduction

Traditionally, power systems analysis has been performed within software that is specifically tailored to the needs of an engineer. These tools are highly successful and satisfactory for the calculation of load flow, protection settings, short circuit analysis, harmonic analysis, etc. In addition, it is important to recognize that the information required to perform these calculations is also utilized in other forms of system management. For example, to establish protective device settings for a distribution feeder, an engineer needs to know attributes such as cable length, configuration, material, and size. Likewise, a power system manager, involved in planning for expansion, needs to know the very same information on the feeder to determine the available capacity for growth. In large part, this is a database function and can be served from a business-wide information system [1].

To take this notion one step further than a traditional relational database, the idea of locational or spatial information can be incorporated. No information system handles this better than a Geographical Information System (GIS). Organizing information in a GIS satisfies the need for data storage and accessibility just like other information systems. However, GIS is built from a mapping foundation and thus creates a visual interface to the data. In addition to normal database queries, information can be examined through a variety of spatial attributes such as distance, proximity, and elevation (to name a few).

Another function that sets GIS apart from simple columns and rows is its ability to integrate information from a variety of sources. For example, a traditional power system database could answer many specific questions on an electrical distribution system. However, it may not be able to address the system’s interaction with its surroundings. For instance, in planning the installation of a distributed generator there are certain environmental, social, and infrastructure-related criteria needed to fully assess the situation [2]. In a GIS environment, these factors would be virtual layers of information that are “draped” over the existing electrical system as in Figure 1.1. There is no better way to visualize this scenario than within the mapping environment. This thesis illustrates the extended capabilities that GIS provides to traditional power system engineering analysis techniques.
1.1 Overview of Geographic Information Systems

Geographic Information Systems come in all shapes and sizes. Some are project-specific and support a single initiative for a fixed period of time. They may be primarily utilized for presentation purposes due to their spatial analysis or cartographic capabilities. Other, more dynamic systems have the capability of relating vast amounts of information through database functionality, as well as spatial analyses. These systems are often built around data that may be created and maintained by different people in various environments. With proper coordination and database design, all information (including database, imagery, video, spatial, etc.) can be linked through map graphics that ultimately tie back to a location on the earth’s surface. Essentially, regardless of scale, a GIS is a container of information that can be extracted through a map view. The old adage, “a picture is worth a thousand words,” is a simple description of the effectiveness of GIS in communicating or expressing complicated information in a highly intuitive manner.

Environmental Systems Research Institute (ESRI), the world leader in Geographic Information Systems’ technology, defines a GIS as “an arrangement of computer hardware,
software, and geographic data that people interact with to integrate, analyze, and visualize data; identify relationships, patterns, and trends; and find solutions to problems. The system is designed to capture, store, update, manipulate, analyze, and display the geographic information. A GIS is typically used to represent maps as data layers that can be studied and used to perform analyses.”

ESRI offers a suite of scalable GIS tools that can be utilized in virtually any application. ESRI’s tools address desktop analysis, mobile needs, web delivery, programming/development, and a variety of customized extensions. The integration of various data sources and the structure necessary to manage these types of systems is handled in GIS by a data model called the geodatabase. Its basic structure and components of this “geographic” database can be seen in Figure 1.2. This research focuses on a geodatabase solution and it highlights the ability of GIS to integrate data that is traditionally maintained in a different environment. Also, this work illustrates the added capabilities achieved through modeling an electrical distribution system in GIS.

![Figure 1.2: The ESRI geodatabase architecture (courtesy ESRI)](image-url)
1.2 Purpose of Study

It is the intent of this study to explore the data exchange between a Geographic Information System and a power system analysis toolset. In today’s day and age, most facility infrastructure information is maintained in some form of database or information system. In many cases, these attributes are stored in a central data repository capable of managing an enterprise type system, which is defined by ESRI as a system that “supports strategic business decisions or large databases across multiple departments in an organization.” One such arrangement, referred to as a Geographic Information System, provides a robust relational data structure, coupled with a spatial (mapping) component. These systems are often used to manage and share information across disciplines or between departments through a map interface.

This thesis documents a specific application of GIS to common power system engineering practices, whereby information inherent to a GIS model provides the necessary input data to run a load-flow analysis within an external engineering software package. As indicated by L.V. Trussel, there are four reasons why GIS is a capable source of data to feed engineering analysis in many utilities [3]:

1) GIS is commercially available in industry standard software (like AutoCAD®);
2) GIS can manage a broad swath of information across department lines;
3) The use of XML and open source database technologies enables sharing;
4) Reporting can be accomplished through standard web-interfaces.

In addition to feeding the load-flow model, the engineering results will be returned into the spatial (graphical) mapping display within the GIS. This exercise will showcase the interoperability of GIS and highlight the flexibility it possesses to extend into the technical realm of engineering.

1.3 Research Goals and Approach

This thesis presents the application of Geographic Information Systems to the engineering of electrical distribution systems. Currently, customized solutions exist for this integration. There are engineering software packages capable of utilizing GIS display
capabilities and conversely, there are customized GIS extensions aimed at capturing engineering toolsets. However, this research presents an integration solution using basic GIS software that is readily available and currently in place at most businesses and universities. Under this premise, the objective of this research includes the following goals:

1. To extend spatial analysis and display capabilities into traditional Power System studies,
2. To apply basic Commercial, Off-the-Shelf (COTS) GIS products to power system analysis,
3. To demonstrate that an existing GIS can provide the necessary data to run load flow analysis,
4. To display and query load flow results in a mapping environment, and
5. To investigate the transfer of information between GIS and an engineering software-package (DistributionSys, Version 4.01).

To achieve these goals, six steps were applied. To start, a geodatabase was constructed to model the IEEE 37-Bus distribution feeder in GIS. From the perspective of an engineer, this model could represent an existing data source, possibly maintained in another branch or office of a business. Next, utilizing this GIS model of an electrical distribution system, data was exported into a format that was compatible with DistributionSys engineering software. Thirdly, load flow analysis was performed within the engineering application. As a follow-on step, the results were incorporated back into the existing geodatabase in the GIS environment. In the fifth stage, the engineering analysis results were queried within GIS, to demonstrate the added capabilities delivered through the integration. As a final step, to demonstrate the passing of information from GIS back to DistributionSys, the engineering model was automatically generated from existing GIS tabular information. The entire information exchange is summarized in Figure 1.3.
Figure 1.3: A schematic summary of the modeling process
2.1 GIS Applications to Electric Utility Power Systems

To obtain a full understanding of the broad capabilities that Geographic Information Systems bring to the realm of electric utility management, it is necessary to recognize some existing applications throughout the industry. GIS systems in large companies often bridge the gap between many different information systems and by their mere existence, provide basic management tools. The following list highlights a variety of specific GIS applications within different electric utilities. It is important to recognize that most, if not all of these applications offer a variety of financial, business, engineering, and construction planning tools inherent to an enterprise GIS solution.

Vegetation Management: To highlight the importance of vegetation management, it is necessary to point out that after the major blackout in August 2003, a bi-national task force (U.S. and Canada) determined that a major factor contributing to the blackout was tree contact with transmission lines. The New York Power Authority (NYPA) has an exemplary vegetation management program in place to protect its 1,400 circuit miles of high voltage transmission lines. This system is an enterprise GIS that ties together information from land management, equipment maintenance, environmental, and engineering disciplines. This tool was developed to help NYPA manage the company’s 16,000 acres of high voltage right-of-way. In the past, NYPA utilized “as-built” construction drawings to delineate the vegetation profiles for right-of-ways. The use of static design drawings to document ever-changing vegetation was difficult to keep current. GIS, coupled with GPS surveying technologies, has allowed NYPA to integrate spatial mapping into the planning of right-of-way maintenance and treatments. It has also allowed managers to compare the effectiveness of treatments from one year to the next. The ability to monitor the effectiveness of treatments has helped NYPA minimize herbicide applications, both saving money and mitigating ecological affects [4].

Land Management: American Electric Power (AEP) utilizes GIS to manage its own 300,000 acres of real estate property. Since its incorporation in 1906, AEP has managed its land transfer records on paper, organized in file cabinets. This system has been made more
efficient by organizing these records and new transactions into an enterprise GIS. Property boundaries are now maintained in a digital format and are no longer hand-drawn. Extensive field surveys are no longer needed to close a sale on land since the property boundaries are readily available and accurate. This function is highly valuable because in the past, the profit made on land transfers was often offset by the cost in time and money of surveying their own property boundaries. This application of GIS technology helps distribute important real property information to the company’s real estate agents, legal, and other personnel via the AEP intranet [5].

Emergency Management: Dominion Electric’s GIS provided important disaster management support in September 2003, during Hurricane Isabel. During that storm, more than 1.8 million customers (out of 2.2 million, total) in Virginia and North Carolina lost electrical power. Dominion’s enterprise GIS provided support during the hurricane by tracking damages, analyzing outages, prioritizing work orders, and organizing logistics for the recovery effort. This GIS system had been built in previous years to support outage management, feeder connectivity, engineering plat production, and overall asset management. Its role in restoring power to Dominion’s customers increased down time by streamlining the response to this disaster. In addition, Dominion provides a web-based GIS service delineating current outages in the company’s service area. This tool was used 650,000 times during the two-week Isabel recovery and is an example of how utilities are using GIS technology to disseminate important information [6].
Environmental Management: The Companhia Paranaense de Energia (COPEL) in Brazil utilizes GIS as a planning tool to address its interaction with the local environment. The Brazilian state of Parana maintains environmental regulations enacted to protect forested areas, to prevent erosion, to maintain agrarian fertility, and to mitigate pollution. COPEL adopted an environmental management tool that utilizes GIS to help manage the company’s environmental compliance.

COPEL is a large electric utility that owns 18 power plants, 17 of which are hydroelectric. The utility’s decision makers utilize this system to weigh the costs versus benefits when faced with planning the location of new hydroelectric facilities. COPEL’s environmental GIS allows the utility to consider demographics, health, and environmental effects when planning for expansion or growth. In addition, this system allows dam water management and provides for the relocation plans necessary during the construction of a new hydroelectric power plant. This system was tested recently during the construction of a new hydroelectric facility where it created the contingency plans for damage to the dam [7].

2.2 Engineering Analysis within GIS

In the current state of the industry, electric utilities are faced with ever-increasing competition. They are required to produce more power, at higher reliability, with fewer planning staff. Oftentimes, GIS is a system that enables greater corporate efficiency through
the effective sharing and distribution of information. Utilities that have mature data processes and good corporate information systems can compete more effectively in today’s market. Furthermore, those businesses that have sound information systems can leverage existing data to support engineering analysis (as well as other specific applications). Utilizing existing corporate information is the logical choice to avoid redundancy and synchronization issues. Therefore, in utility environments that have existing GIS, it makes good business sense to integrate engineering analysis within the envelope of the corporate information system structure.

Within a utility’s corporate information system, engineering applications demand the highest quality, and the most specific datasets. In addition to utilizing information that is common to the business model, engineering analysis also requires data that may not normally reside within the GIS. As indicated by Trussell and Kenney, any integration of GIS and engineering analysis will require implementation of network tracing, data conversion, validation, additional engineering parameters, and software execution [8].

There are a variety of ways to integrate GIS and engineering analysis. The most basic technique, data extraction, will be utilized in this research. Extraction refers to drawing information from the GIS, supplementing it with the data required by engineering analysis, and exporting it to its own database. This approach provides the engineer with total control of the information, but presents maintenance problems because any changes made by the engineer aren’t incorporated back into the enterprise data system [8]. It is important to recognize, though it is beyond the scope of this work, that a variety of integration scenarios exist to automate this process on an enterprise level. Some of these integrations are packaged in proprietary software solutions and will be summarized in the following section.

2.3 Existing Integration Solutions

The goal of integrating GIS and engineering analysis is to create technically valid reporting capabilities within the GIS environment. As indicated in the previous section, there are a variety of integration solutions available that are scalable to specific needs.

From a GIS vantage point, there exist commercially-available, custom solutions for integrating engineering capabilities through ESRI partners. For example, Miner & Miner offers ArcFM®, a powerful extension to basic GIS. This extension is an enterprise solution tailored to the needs of utility system management. Engineering capability exists within the
extension to interface the infrastructure model with “third-party” engineering analysis engines. The “Network Adapter” to ArcFM® allows an engineering model to be extracted from the existing GIS data and loaded via XML into the analysis engine. Also, it allows for the flow of information back into the GIS, in the opposite direction. In essence, this tool provides an interface between the GIS and the engineering analysis software package. The model templates are structured to work with ESRI’s Electrical Distribution data model and interface with common analysis packages such as CYME's CYMDIST®, Advantica Stoner's Electric Solver®, and Milsoft's Windmil® (used for load flow on IEEE test feeders [9]).

From a power systems analysis perspective, there also exist solutions designed by the software vendors to integrate their engineering analysis tools with GIS. For example, Siemens Corporation offers engines to extend the traditional power systems analysis capabilities of PSS/E® into the realm of GIS. PSS/Engines® contain the algorithms necessary to perform different analyses of electrical distribution networks. These engines can be called from virtually any programming language, including Visual Basic, the common language of the current ESRI ArcGIS® platform.

There are many examples of customized integration solutions on the market today. However, the scope of this research will focus on a non-proprietary, basic GIS integration using tools that are readily available at most businesses or universities.

2.4 Distribution Management System Data Standards

With the onset of deregulation and under heightened competition, utilities are facing great challenges in the exchange of distribution system information. Energy management systems (EMS) are often employed to model transmission systems and have matured greatly to support such critical infrastructure. However, the demands of distribution management are quite different and require more information for a variety of reasons. Primarily, distribution systems have very large information models, and as a result, require tracking and accounting for many more system components. Distribution systems data models are also larger in size, having on the order of 500,000 to 10,000,000 objects [10].

Adding to the complexity, there are many different system interactions. For example, a distribution management system (DMS) needs to incorporate a customer information system, a geographic information system, an outage management system, a
maintenance tracking system, as well as many more applications to effectively manage the delivery of electricity to its customers.

In addition to the amount of information and the broad variety needed, system changes occur more frequently in distribution systems when compared to transmission networks. There are constant maintenance changes that need to be tracked as well as operational/control modifications in distribution systems. The DMS needs to be flexible to reflect the ever-changing conditions inherent to an electrical distribution system.

The magnitude and complexity of the data required to manage a distribution system warrants its own standard. As is with most Distribution Management Systems, the sub-systems and their respective datasets often reside in proprietary software packages. This presents a problem in the effective exchange of information across departments. To design and implement a streamlined enterprise information system for utility system management, there needs to be standard data model for distribution networks. This standard provides a target for software development and interoperability. It also integrates both engineering and business functions. The Common Information Model (CIM) is currently being applied to distribution systems and standardized through the International Electrotechnical Commission (IEC) [10], [11].

### 2.4.1 Common Information Model (CIM)

The Common Information Model was originally developed by the Electric Power Research Institute (EPRI) as a framework for an integration called the Control Center Application Program Interface (CCAPI) [10], [11] [1]. This model was constructed to integrate the control center environment with business functions by facilitating the information exchange between different computer systems and applications. The Common Information Model (CIM) was a large part of this standard and was originally representative of information inherent to transmission networks. As the need for a modified distribution system data model became more evident, the IEC Technical Committee 57 Working Group 14 took on the task of standardizing an information model for “Systems Integration for Distribution Management (SIDM).” The prefacing work to standardize the CIM for energy management systems resides under the purview of Working Group 13. Websites dedicated to these working groups are available at the following locations:
The CIM is a logical data model that provides a framework and theory for the various relationships of distribution system information. The actual physical implementations of this model are vendor specific and may vary. In addition to developing a standard model, it is very important to develop the physical tools that coordinate data for import and export in accordance with the CIM. Xiaofeng Wang has proposed modifications to the existing CIM to extend the model into distribution realm for load flow capabilities. This work takes the IEEE Feeder Models [9] developed by Professor Kersting and adapts them to the CIM as extensible markup language (XML) documents. Though Geographic Information Systems are considered by the IEC as sub-systems within the CIM, many of the modeling issues identified by Wang parallel those experienced through this research. The modeling in this project was not in accordance with the CIM, but the techniques and the data model indicated in Wang’s work were referred to throughout the entire process. Wang modeled the IEEE Feeders in XML and it is the intent of this work to do the same in a graphical manner through the GIS [10].

2.4.2 Other Data Models

It is important to recognize the existence of multiple standards for the modeling of electrical distribution systems. The aforementioned data model is a product of the IEC and is geared toward the international implementation for electrical utilities. The CIM structure encompasses both technical and business functions into one enterprise level information system typical for utilities. This model addresses the management of immense amounts of information and views GIS as an Automated Mapping/Facilities Management tool.

In addition, ESRI maintains an electrical distribution system data model to support engineering, construction, and operational needs. This model focuses primarily on infrastructure management. It is tailored to the needs of management, operations, and maintenance of the infrastructure life-cycle to help maintain current as-built information. It intends to integrate computer-aided design (CAD) drawings with the GIS network as well as providing integration capabilities with other systems responsible for managing outages, documents, materials, customer information, et cetera [12] [1].
Another standard data model available for system representation is the Spatial Data Standard for Facilities, Infrastructure, and the Environment (SDSFIE). This logical data model was developed through a cooperative effort between the three U.S. Department of Defense military services (Army, Air Force, and the Navy). Its original intent was to provide a standardized model for federal facilities management information. It evolved to include a broader vision of dissemination beyond the Department of Defense and federal facilities. The Facilities Management Standard for Facilities, Infrastructure, and the Environment (FMSFIE) portion addresses the management of enterprise level information that relates to the infrastructure data. The SDSFIE is a spatial data model and primarily addresses features that have been mapped in either the CAD or GIS environment. This model is tied to the FMSFIE through valuable relationships inherent to virtually any organization charged with the management of facilities. These standards offer more than theoretical data models. The strength of this format lies in the availability of non-proprietary tools. This standard offers free tools for the construction of empty GIS data as well as the construction of a “skeleton” relational database structure. The published tools are updated frequently and provide the import/export toolset imperative to the success of a large implementation [13], [14], [15].

The work documented in this thesis does not adhere to any one standard, though it pulls logical modeling techniques from the standards referenced above. It is beyond the scope of this work to compare the pros and cons of these modeling approaches. However, further work could be undertaken to investigate the differences.
Chapter 3 – Modeling 37-Node Network in DistributionSys 4.01

3.1 DistributionSys

DistributionSys 4.01 is an electrical distribution analysis software package developed by Dr. Alexis Martínez del Sol of the University of Guadalajara, Mexico. This software allows for the modeling of distribution system components and provides the analysis tools necessary to perform standard engineering calculations such as load flow, bus voltage, transformer loadability, and protection analysis.

Network models can be built within DistributionSys from a schematic view or from existing attribute data. The software is capable of importing and exporting information from Microsoft Excel, making it a good candidate for GIS integration. In addition, the object-oriented model can be built from a customizable catalog of system component information.

DistributionSys is capable of calculating balanced and unbalanced load-flow. This analysis produces both detailed and summarized accounts of system losses, line flows, and voltage at every node or bus. The software is capable of recommending optimum capacitor placement, wire size upgrades, and changes in conductor configuration to satisfy user-defined restrictions on the system. DistributionSys contains a tool to calculate maximum and minimum short-circuit current at system nodes as well as the ability to analyze protection settings. The software can check the coordination of settings against a given scenario and identify uncoordinated devices.

Once a system is modeled correctly in DistributionSys, the analysis tools available enable a wealth of capability. Since the output results from these analyses can be exported to Excel, they can be displayed in a GIS environment to further extend the reporting capabilities. Conversely, since the system models can be built from an Excel template, an existing GIS model (if formatted correctly) could provide all of the information necessary to automatically build a network model in DistributionSys [16].

3.2 Modeling Methods
System models can be created through a graphical-user-interface or by importing system information from a spreadsheet. If designed graphically, the system is drawn node-by-node or line-by-line. The specific parameters can be entered for each component and can be either selected from a standard catalog of equipment or customized to fit the particular system component. The following screenshot demonstrates the graphical modeling option:

![Graphical Modeling in DistributionSys](image)

Figure 3.1 Graphical Modeling in DistributionSys

Electrical distribution system models can also be developed automatically within DistributionSys by importing system information through the standardized Microsoft Excel template (provided as an ancillary file with full installation). This template provides the spreadsheet structure that the software can recognize. Once the correct cells and worksheets are populated with system information, the template can be imported into DistributionSys and a model can be automatically generated. The template is an Excel file of extension “.xls” and is formatted such that each feature (i.e. line, load, bus, transformer, etc.) has its own spreadsheet on a separate “worksheet”. “Worksheets” are delineated as tabs across the bottom of an Excel spreadsheet. The following figure is an example:
The modeling procedure within DistributionSys is greatly simplified by the existence of its “Standard Catalog.” This is a database of common system information that includes cable configurations, transformer connections, equipment ratings, voltage levels, and other standard attributes. This feature allows a user to select equipment that already has defined electrical parameters. For example, when modeling overhead powerlines, a user may select from dropdown menus, a set of aerial, three-phase, ACSR 477 conductors with a certain pole-top spacing configuration. Using this information and the length of the line, DistributionSys estimates the impedance by calculating the line’s phase impedance matrix. The information contained within the Standard Catalog greatly simplifies the modeling procedure. In addition, the catalog can be modified to add unique components or to change the characteristics of existing attributes. The “Standard Catalog” can be seen in Figure 3.3.

3.3 IEEE 37-Node Feeder Model
3.3.1 Overview of IEEE Feeder Models

In 1992, the IEEE Distribution Analysis Subcommittee published a report providing five benchmark electrical distribution system models. These models were developed to provide a common set of system information for software developers to test and verify the accuracy of engineering solutions. Detailed equipment information is included in the report as well as the solutions to various power system analyses. All solutions were performed using the Radial Distribution Analysis Package from WH Power Consultants and/or Windmil® developed by Milsoft Integrated Solutions [9].

The 37 Node Test Feeder model was selected as the system of choice for this research. It represents an actual underground radial distribution feeder in California operating at 4.8kV under heavy phase imbalances. The schematic view of this network can be seen in the following figure:

![IEEE 37 Node Test Feeder network schematic.](image-url)
All loads on this system are modeled as “spot” loads (some other IEEE models contain continuous, or distributed loads). Table 3.1 contains the various types of load models found in the IEEE radial distribution feeder systems.

<table>
<thead>
<tr>
<th>Code</th>
<th>Connection</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-PQ</td>
<td>Wye</td>
<td>Constant kW and kVAR</td>
</tr>
<tr>
<td>Y-I</td>
<td>Wye</td>
<td>Constant Current</td>
</tr>
<tr>
<td>Y-Z</td>
<td>Wye</td>
<td>Constant Impedance</td>
</tr>
<tr>
<td>D-PQ</td>
<td>Delta</td>
<td>Constant kW and kVAR</td>
</tr>
<tr>
<td>D-I</td>
<td>Delta</td>
<td>Constant Current</td>
</tr>
<tr>
<td>D-Z</td>
<td>Delta</td>
<td>Constant Impedance</td>
</tr>
</tbody>
</table>

Table 3.1: IEEE Feeder load models.

Loads are delineated as delta or wye connection and as constant power, impedance, or current. Constant impedance and current loads are determined by assuming a system voltage of 1 per unit. The 37-Node Feeder is configured as a three-wire delta system and therefore has no wye connected loads. It does, however, have many different line-to-line loads that contribute to unbalanced conditions.

All conductors in the 37-Node model are assumed to be of the three-wire, delta configuration. In addition, they are buried underground with a Spacing ID of 515, corresponding to configuration in the following figure:

![Figure 3.5: Underground Line Spacings](image)

Conductor line segment data contains “from” and “to” nodes as well as the actual cable length per phase between nodes. The total result of this data plus individual conductor sizes provides for the calculation of phase impedance and admittance matrices, a fundamental part of distribution system analyses.

3.3.2 Structure and Format
For the purposes of this research, the GIS model is built from existing tabular data provided by the IEEE 37 Node Feeder model. The data is available from the report in the form of excel spreadsheets and can be found at the following IEEE URL:

http://ewh.ieee.org/soc/pes/dsacom/testfeeders.html

The tabular datasets provide all of the information necessary to perform standard power system analyses such as load flow, bus voltage, and line current calculations. It is important to recognize that when maintained within GIS, this model isn’t limited to engineering analysis. The GIS model of the distribution system can easily integrate other data sources to allow applications such as those mentioned previously in Section 2 (operations and maintenance, outage response, environmental, dig permitting, etc) [15].

3.4 Modeling IEEE 37-Node System Elements

3.4.1 Source

The IEEE 37-Node system was modeled in DistributionSys to enable its analysis and reporting capabilities. The system of interest, as introduced in Section 3.3.1, was a 4.8kV network configured delta and distributed underground in a three-wire configuration. The IEEE system source is designated as two single-phase regulators, configured as open delta. The following table summarizes the regulator information.

<table>
<thead>
<tr>
<th>Regulator Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulator ID:</td>
<td>1</td>
</tr>
<tr>
<td>Line Segment:</td>
<td>799-701</td>
</tr>
<tr>
<td>Location:</td>
<td>799</td>
</tr>
<tr>
<td>Phases:</td>
<td>A - B - C</td>
</tr>
<tr>
<td>Connection:</td>
<td>AB - CB</td>
</tr>
<tr>
<td>Monitoring Phase:</td>
<td>AB &amp; CB</td>
</tr>
<tr>
<td>Bandwidth:</td>
<td>2.0 volts</td>
</tr>
<tr>
<td>PT Ratio:</td>
<td>40</td>
</tr>
<tr>
<td>Primary CT Rating:</td>
<td>350</td>
</tr>
<tr>
<td>Compensator Settings:</td>
<td>Ph-AB</td>
</tr>
<tr>
<td></td>
<td>Ph-CB</td>
</tr>
<tr>
<td>R - Setting:</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>X - Setting:</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Voltage Level:</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>122</td>
</tr>
</tbody>
</table>

Table 3. 2: IEEE 37-Node Regulator data

For the purposes of this research, the regulator was modeled in DistributionSys as a substation consisting of a lossless, three-phase transformer (4.8kV/4.8kV) connected to a
source of infinite short-circuit current. The lossless transformer’s kVA rating and the available fault current were set unrealistically high to act as infinite.

### 3.4.2 Nodes

All 37 nodes from the IEEE system were modeled in DistributionSys as primary nodes. As they were drawn in graphically, the software assigned coordinate information to the nodes based on their location in the Cartesian grid. This feature is important to recognize since the idea of locational coordinates is inherent to a GIS model. When drawn in DistributionSys, the network busses are assigned Cartesian coordinates (Figure 3.6) and the resulting product is an unscaled network schematic. When the model is built in GIS, the coordinates are referenced to the earth’s surface and act to scale the entire network so distance and direction between nodes becomes meaningful.

![Figure 3.6: DistributionSys Cartesian coordinates assigned to nodes.](image)

### 3.4.3 Lines

Conductors were modeled as they had been in the IEEE to be separate line segments between nodes. To simplify the transition to GIS, the conductors were given a name based on the upstream and downstream nodes. The format follows the convention of combining the names of “from node” with “to node” into one, unique, six-digit code for every line. Since the system is entirely radial, this naming convention works for every line in the system and will provide the bridge between DistributionSys and GIS for displaying line losses, and line power flows. Table 3.3 displays a tabular snapshot of line attributes exported from DistributionSys into Excel.
Table 3.3: Excerpt of line attributes output from DistributionSys.

All lines were modeled as three-wire delta, no neutral. The configurations were assigned based on those given in the IEEE 37-Node model. The four different cable configurations were entered into the DistributionSys “standard catalog.” Since they were added to the database, their electrical parameters were also estimated and logged.

Table 3.4: Summary of cable configurations used in model.

In table 3.4, columns “Config.”, “Conductor”, “Type”, “R(ohms/mile)”, “Diam.(in)”, “GMR(Feet)”, and “Rating (A)” were all provided by the IEEE excel tables. “Microsiemens per mile” were taken from the estimated admittance matrices generated by Milsoft software. This value corresponds to the capacitive admittance observed in underground conductors. In DistributionSys, the parameter used to estimate the capacitive reactance in underground conductor configurations is picofarads per meter. Therefore, column “C (pF/m)” is simply the capacitance per unit length converted from the admittance at 60 hertz using the following equation:

$$\frac{pF}{m} = \left[ \frac{\mu S \cdot mile}{1609 \cdot 10^6 \mu S \cdot (2\pi \cdot 60)S \cdot F} \right] \cdot \frac{10^{12} \ pF}{F}$$
Inductive reactance per unit length was calculated using conductor spacing information (per Figure 3.5) and the Geometric Mean Radius (GMR) from the table above. The equation is as follows [17]:

\[
\frac{\mu \Omega}{m} = \left[2\pi \cdot 60 \cdot 2 \cdot 10^{-7}\right] \cdot \ln \left[ \frac{3^{1/2} \cdot 6'' \cdot 12''}{GMR(\text{ft}) \cdot \frac{12''}{\text{ft}}} \right]
\]

As a check, the calculated reactance values were on the same order of magnitude as those given by DistributionSys for similar (but not exact) conductor types and configurations. DistributionSys contains values for underground 1000MCM, 500MCM, 2/0, and #2 XLP three-phase conductors of unknown spacing. The comparison is summarized in the following table:

<table>
<thead>
<tr>
<th>General Underground Cable Type</th>
<th>Calculated microhms/m</th>
<th>Pre-Determined microhms/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 MCM AA</td>
<td>214.03</td>
<td>237.70</td>
</tr>
<tr>
<td>500 MCM AA</td>
<td>240.21</td>
<td>266.00</td>
</tr>
<tr>
<td>2/0 AA</td>
<td>295.41</td>
<td>318.10</td>
</tr>
<tr>
<td>#2 AA</td>
<td>321.60</td>
<td>347.00</td>
</tr>
</tbody>
</table>

Table 3.5: Comparison of cable reactance estimates.

Calculated values were used to create new conductor configurations within the Standard Catalog of DistributionSys. Their comparison serves as a check against the validity of the model to ensure practical results but does not intend to match exactly with the IEEE feeder model. The goal of this research is to utilize GIS for display and to demonstrate the enhanced capabilities that GIS provides. Testing with the IEEE model to exactly match results is not the intent of this undertaking.

3.4.4 Loads

All loads from the IEEE 37-Node Feeder system were modeled as either constant current, constant impedance, or constant power loads. These demand types were entered into the Standard Catalog of DistributionSys under load profiles. Since the software allows for varying loads over the course of the day, the IEEE loads were modeled as continuous and delineated as either constant current, constant impedance, or constant power (See Figure 3.7)
3.4.5 Transformers

Modeling transformers in DistributionSys in accomplished in the representation of loads. When a load is added to a particular bus, the user is prompted to choose the type of transformer and its particular connection. In addition, when modeling primary loads within the software, the user also identifies the type of load (from above; Section 3.4.4). For this research, all the transformers and loads were entered in advance into the Standard Catalog to simplify the modeling process. Transformers were modeled as lossless, 4.8kV/4.8kV delta connections. All loads (though three-phase) were modeled as single-phase transformers and loads. Breaking the loads up by phase simplified the modeling process since the IEEE network was created to simulate heavy phase imbalances. For example, this idea is illustrated in Figure 3.6 where the three-phase, constant-PQ load attached to bus 701 is split into three separate loads. Each load is attached through a lossless, 4.8kV/4.8kV delta transformer and has a continuous demand at rated load. Each load is designated to be connected across its respective phases and as a result, it is applied as intended by the IEEE model.
3.5 Load Flow Results

Load flow results from DistributionSys can be exported in tabular format. For unbalanced load flow, line current and phase angle is given for all three phases. Total real power losses and kilowatt-hour losses are given per line but are lumped into one total measurement that is combined for all three phases. Reactive power flow and losses aren’t given, but can easily be calculated from the output information. For balanced flow, results are similar, but as expected, line currents and angles are lumped into one, single-line measurement.

The format of the output is manageable with some minor adjustments. For example, bus voltage, line losses, and summary calculations are placed on the same excel worksheet even though they don’t have the same column/row structure. Therefore, to make use of this information, it must be manually regrouped by “cutting and pasting” the individual datasets to separate files. For this research, the effort is minimal. However, for a large power system with many nodes and multitudes of data, an automatic separation would be necessary. In addition, to automatically interface with a GIS, the information would need to
be formatted in this way. One possible solution to this problem would be to output in a relational database structure such as Microsoft Access. This could be directly read into GIS without any human manipulation, thus minimizing the possibility for error.

For the purposes of this study, the bus voltages and line flow information will be separated into dBASE tables for both balanced and unbalanced simulations. In the end, there will exist a total of four tables containing load flow information from DistributionSys. These tables will be added to the final geodatabase for interaction and visibility into the GIS network model.
Chapter 4 – Modeling 37-Node Feeder in GIS

ESRI defines a shapefile as “a vector data storage format for storing the location, shape, and attributes of geographic features. A shapefile is stored in a set of related files and contains one feature class.” This file structure served as the basic building block for this research exercise. The locations of the equipment were arbitrarily selected and digitized over an aerial photo. As they were drawn, they were given a name that uniquely identified each feature. As applicable, this information was transferred directly from the IEEE model. Once the shapefiles were produced, each feature had a record containing locational information and its unique name. Since the attribution already existed in tabular format within Microsoft Excel, it was easily “joined” to the respective shapefile’s database according to the unique identifier. In the end, shapefiles were created for each equipment group. Table 4.1 summarizes the shapefile structure and the datasets that were utilized to build each file. These shapefiles were used to build the final geodatabase and the Geometric Network.

<table>
<thead>
<tr>
<th>Shapefile</th>
<th>IEEE File Name</th>
<th>IEEE File Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductors.shp</td>
<td>Line Data.xls</td>
<td>UG Config.xls</td>
<td>Conductors Data.xls</td>
</tr>
<tr>
<td>Loads.shp</td>
<td>Spot Loads.xls</td>
<td></td>
<td>All spot loads with correct corresponding IEEE names</td>
</tr>
<tr>
<td>Nodes.shp</td>
<td>Spot Loads.xls</td>
<td></td>
<td>Spot loads plus other network junctions without loads</td>
</tr>
<tr>
<td>Regulator.shp</td>
<td>Regulator Data.xls</td>
<td></td>
<td>Modeled as the system source</td>
</tr>
<tr>
<td>Transformer.shp</td>
<td>Transformer Data.xls</td>
<td></td>
<td>Included but not utilized in this research (assumed lossless)</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of shapefiles and supporting datasets

The following illustration summarizes the methods and procedures detailed in this chapter:
4.1 Spatial Graphics

Since all GIS models are inherently dependent on spatial information, locating the equipment in the IEEE system model served as the primary step towards building a geodatabase. The IEEE 37-Node schematic contains topological information on the connectivity of network system components. In addition, the model encapsulates equipment attribution in the form of tabular data or spreadsheets. However, as it exists, the IEEE model doesn’t pinpoint the locations of various electrical system components. There are no geographic coordinates for the locations of the 37 nodes in the system or for the cables connecting them. Therefore, for the purposes of demonstrating the model in a GIS environment, arbitrary locations were assigned in true geographic space.

As an initial step, all 37 nodes were digitized (or drawn) to empty shapefiles over a randomly-selected aerial photo. In addition, the various feeder configurations connecting these system nodes were added in the same fashion. For the purposes of this research, the conductor configurations were modeled as single lines representing all three phases. Ideally, the best way to fully model a distribution system under unbalanced conditions is to create a separate line for each phase of the cable configurations. The choice to model the system as single lines was made to strike a balance between map clarity and functionality.

Creating a spatial reference for the IEEE system components within the GIS environment allows for distance measurements and for coordination with other layers.
Once a model is locked into its correct geographic space, other layers of information can be added for subsequent analysis. Also, the layer itself can be utilized in other geographic projections since GIS supports “on-the-fly” geographic projections. For example, an electrical engineer having problems with pad-mounted transformer grounding could overlay soils (created by someone else for agricultural purposes) on top of a transformer layer to help understand the ohmic variations around each grounding grid. Simply put, spatially referenced GIS layers can be shared in a variety of ways between different disciplines and across platforms. Assigning spatial reference to the IEEE 37-Node Feeder model sets the foundation for GIS modeling of this system.

4.2 Attribution

The second step in building the GIS model concerned incorporating tabular attribution from the IEEE spreadsheets. As indicated in Chapter 3, this information exists in an open format in Microsoft Excel and is accompanied by a detailed written description. The attribute information was exported from .xls to dBASE format to allow operability in the GIS software. Once the dBASE files were imported into the GIS, they were joined based on unique identifiers. Figure 4.2 illustrates the concept of joining tabular datasets based on a common field or “unique identifier.” This process was performed within the GIS, appending detailed columns of attribution to the base mapping layer. This step simplified attribution by eliminating manual data entry. The records of interest were already maintained in the IEEE excel spreadsheet.

![Figure 4.2: Joining attribution to shapefiles](image)
In the case of the conductors’ layer, there exists more than one spreadsheet of attributes. A tabular join greatly simplifies the system information by eliminating redundancy and accumulating all data into one file. The following data was condensed into one table for simplification and joined to the shapefile containing the spatial graphics which represent lines:

1) Cable configurations identified by “from” node and “to” node
2) Conductor spacing by configuration
3) Conductor details by configuration
4) Cable configuration ampacities

Figure 4.3 and 4.4 display the 37-Node model attributes in the GIS environment. These figures illustrate different methods of display that can be utilized for visual or tabular analysis.
Figure 4.3: GIS display of conductor type
4.3 Building a Geodatabase

As illustrated early in this paper in Figure 1.2, a geodatabase is a virtual “container” for various types of information relevant to a GIS. It provides an organizational structure for a variety of data sources and provides a level of intelligence to help manage this information. In addition to assisting data management, a geodatabase also extends GIS functionality. One example that is relevant to this project is the ability to create Geometric Networks (to be detailed in Section 4.4).

Building a geodatabase for this project required some data conversion and minimal formatting. The shapefiles that represented conductors, nodes, loads, and the source were exported to individual feature classes using ESRI tools. This category of GIS layers can be likened to the shapefile for the geodatabase structure. Shapefiles were exported to feature classes with no data alterations to note. After the conversion, they were loaded into the

Figure 4. 4: GIS display of conductor ampacity
geodatabase. Once the basic layers resided in the geodatabase, feature datasets were created. The feature dataset is another level of organizational structure that allows the added functionality of network building and strictly enforces the precision of grouped, spatial datasets.

Figure 4.5 displays the exact structure of the geodatabase utilized in this research. It should be noted that the engineering results from DistributionSys were stored as dBASE files within this structure (“bal_bus_kV”, “bal_line_results”, “unb_bus_kV”, and “unb_line_results”). Also, the feature dataset entitled, “Backup” was maintained to provide an original copy of the foundational feature classes in case their participation in the network created any unwanted results. The ancillary feature class, “hotlink” is simply a reference layer containing an unscaled IEEE network schematic in windows bitmap format (as seen in Figure 3.4).

![Figure 4.5: IEEE 37-Node Geodatabase Structure](image)

### 4.4 Building a Geometric Network

Once the datasets were loaded into the geodatabase, they could then participate in a special relationship called a geometric network. A geometric network is defined by ESRI as "topologically connected edge and junction features that represent a linear network such as a utility or hydrologic system. The connectivity of features within a geometric network is based on their geometric coincidence. A geometric network does not contain information about the connectivity of features; this information is stored within a logical network. Geometric networks are typically used to model directed flow systems."

The network for the 37-Node system was created using ESRI’s “Build Geometric Network Wizard.” This application prompted the identification of sources and sinks, line impedances, and flow direction. Once the model was built, the IEEE layers became
Topologically related and queries were extended beyond the tabular realm into that of network tracing and connectivity. For example, without the network, one could query the conductors layer for all cable segments greater than 100 feet in length, that are either 1000 MCM or 500 MCM. After the network was built, the same query could be performed plus the additional selection of all items downstream of Node 722. The potential for analysis capabilities was extended to include the network tools to the right.

The only limitation encountered with the geometric network was that the layers making up the network were “frozen” and couldn’t be dramatically changed without creating an entirely new network. In addition, snapping features together proved problematic at times. In order for the network to possess proper connectivity, all of the line segments had to be “snapped” directly to their respective nodes. The network wizard tool allowed for automatic snapping within a given tolerance. However, the success of the snapping wasn’t apparent until after the network had been completely built. The limitations encountered were minor compared to the overall results produced. This tool allowed more for accurate modeling of power system networks by introducing the topological behavior into the network model.

The following figure shows current flow directions and node labels indicating the name and the attached load model (if any). Flow directions were assigned manually to the line segments based on the digitized direction. Digitizing these lines in a downstream fashion during the creation of the original shapefile greatly reduced the amount of time required to assign flow direction to this network. This tool allows for flexibility and could extend the modeling capabilities beyond radial networks into loop connections. In Figure 4.6, yellow arrows indicate current flow direction along the green conductors. The red points represent nodes which are linked to attribution that indicates the loading at each point.
Figure 4.6: Arrows indicating current flow direction and node/load identification.

Figure 4.7 shows the selection resulting from a downstream network trace. Note that the trace stops at the pink “X”. This section of the network was blocked from being selected by a “barrier.” The barrier was temporarily drawn in at that point in the system to represent a break in the line or an open switch. This barrier to flow allows analysis to mimic different operational scenarios. The selection highlights both graphical and tabular components in light blue. Those selected from the attribute database can be exported and handled with normal spreadsheet or database functions. A query like the one shown in Figure 4.7 could provide a list of affected equipment in the event of failure at the bus of origination.
Figure 4. 7: Topological query (downstream trace) with open bus.
Chapter 5 – Demonstration

To this point in the research, detailed attention has been given to the construction of parallel network models, both in GIS and in DistributionSys. Having the network models represented in both systems enables the transfer of information to take place. It allows for the use of each tool (GIS and engineering software) inside its respective area of strength. DistributionSys has been designed around typical power engineering analyses and is the logical choice for modeling these estimates. However, since this software, like most others, allows for the resulting information to be exported in tabular form, engineering calculations can be displayed in map form by exporting to GIS. This situation will be detailed in Section 5.1. Conversely, if distribution system information is managed through a GIS, it can be exported to fulfill the necessary input parameters for engineering analysis. This is shown in Section 5.2.

5.1 Engineering Results in the GIS Environment

Two load flow scenarios were run in DistributionSys. One set of results was produced for balanced load flow and one for unbalanced conditions. The results were, as indicated earlier, formatted in a fashion that required some manual clean-up. These .xls files were re-formatted and saved as dBASE spreadsheets. The final results are seen to the right as they reside within the GIS environment inside of the geodatabase. Resulting dBASE files were created for bus voltage and line flow results for both balanced and unbalanced conditions.

The following scenarios demonstrate a geographic view of engineering analysis results. These figures are representative of the load-flow results displayed and queried within the GIS environment. This capability does not exist with most basic distribution system analysis software packages.

Figure 5.1 shows the loading of conductors throughout the entire distribution system. The line currents were calculated in balanced load-flow conditions within DistributionSys software and imported into the GIS model. Since the GIS network model contained information on conductor configurations and subsequent ampacities, the two
pieces of information were combined to produce a value of percent loading for each conductor configuration in the system. This value is indicative of the assumed load-flow capacity remaining in the existing conductors. This function could be helpful in scenario modeling for planning load growth and for the addition of new customers. In Figure 5.1, the red lines indicate those of highest loading relative to their ampacity ratings. Recognizing the source is to the south and the main cabling serving the entire system is the set running off the image screen, it is obvious that this main feeder is operating at 40-50% of its rated ampacity. In addition, another set of conductors in the middle of the system is also operating between 40-50% of rated ampacity. This conductor is of interest because it is between two segments of cabling that are operating at 30-40% ampacity. If the system load grows by a large amount, this cabling will be the first link in the network to approach its rated ampacity and therefore will be the first candidate for an upgrade. In this instance, as is indicative of many others, the GIS offers this information in a very visual and intuitive fashion. This wire segment essentially “jumps out” at the user and provides a good assessment of the cabling throughout the entire system [18].
Figure 5.1: An example of conductor loading displayed within GIS.

Figure 5.2 represents a combination query that is possible within the GIS environment. The goal of this query is to determine the total real power lost due to
conductor impedance from one point in the system to another. Initially, the conductors in question are selected by graphically picking two points in the system and running a “Find Path” topological query within GIS. This query selected the conductors between the first point and the last. This selection, as indicated by the light blue, automatically selects the graphical features as well as their respective database attribution. As a result, it is then possible to summarize the information on kW loss from the selected set of records. The results of the statistics for the selected set of conductors can be seen in Figure 5.3. The final value for accumulated real power losses due to conductor impedances under unbalanced load-flow conditions is 5.99 kW.
Figure 5. 2: Calculation of accumulated Real Power loss from point to point.
Figure 5.3: Statistics on the real power losses from selected set.

Figure 5.4 shows the display capabilities of integrating GIS with bus voltage results from balanced load flow modeling. The labeled values indicate the percent drop from nominal (4.8kV) voltage at every system bus. These values were generated based on the calculated voltage at each bus and its deviation from system voltage. Figure 5.5 shows the GIS “Field Calculator” and the algorithm used to create a percent voltage drop from nominal value for every system bus. These parameters were calculated within ArcGIS® and stored in a newly created database column. Figure 5.4 utilized this new column to label the busses according to their respective value.
Figure 5.4: Percent voltage drop at every bus. (Calculated from balanced load flow)
5.2 Building Engineering Model from GIS Data

To demonstrate the interoperability of GIS and engineering analysis software, a model was created in DistributionSys directly from GIS tabular information. As indicated early in the research, DistributionSys allows model building in two fashions. To revisit, the system can be drawn graphically with attributes added manually or the model can be automatically generated from an Excel spreadsheet. In this case, the model was built from a fully populated Excel template based on data from the GIS.

Attribution was added manually by cutting and pasting from GIS dBASE tables. Transferring the spatial information was a bit more involved and required scaling the geographic coordinates to numbers acceptable by DistributionSys.

The GIS coordinates existed in the map projection of State Plane Feet. As a result, their magnitude was on the order of 12,280,000 feet for the x axis and 3,780,000 feet for the y axis. Upon the first trial, DistributionSys didn’t recognize the high values of the true
geographic coordinates. Therefore, the numbers were scaled to a value that could be represented on the DistributionSys layout. These changes were successful but highlighted another difference in display. DistributionSys uses a grid that resembles the normal Cartesian type with one major deviation. In the software layout, y values increase going down the vertical axis. In a typical geographic or Cartesian grid, y values increase going up the vertical axis towards geographic north. Figure 5.6 highlights this difference. In an attempt to create a scaled, geographic layout within DistributionSys, the polarity of the y values was changed to negative. This attempt to orient the model to true north was not successful. It is assumed that DistributionSys will accept neither high values nor negative values as component coordinates. This brings to light the fact that the layout in DistributionSys will be “south-up” instead of the typical “north-up” map view.

![Grid comparison](image)

**Figure 5.6: Grids contain different geographic orientation.**

To verify the geographic layout, the system schematic was exported as a bitmap from DistributionSys. This image was added as a raster dataset to the GIS environment. At this point, the bitmap contained no spatial reference, though the graphics it contained were scaled according to their geographic orientation. See Figure 5.7 for evidence of this product.
Producing this image from within the DistributionSys software demonstrates how building the model from existing GIS data extends the display capability of the engineering software. DistributionSys is designed around schematic views of the system. However, using GIS data to populate the template adds a geographic element to the network schematic that it is incapable of producing by itself.

To verify the scaling procedures utilized in this research, the next step taken was to “georeference” the bitmap image for comparison against the GIS network model. Georeferencing is the process by which a raster (otherwise known as a pixilated image) is fixed into its correct geographic space. It is the process by which coordinates are assigned to imagery. In this case, we have a bitmap generated by DistributionSys that has no spatial reference. The intent is to match features (such as nodes) on the bitmap to items on the GIS map. Nodes are the logical referencing points common to the bitmap and the GIS network created earlier in the research. Two nodes were matched to rotate and scale the bitmap in two-dimensional space. Any more than to points would stretch or distort the
image. The intent of this procedure is to preserve the scale and to verify the alignment of the two network schematics. To rectify the problem encountered in the north-south orientation, the bitmap was simply flipped vertically in a basic image editing application. This also flipped the labeling and made it illegible. However, the bus locations were preserved and the methods of scaling proved successful. Figure 5.8 shows the GIS view of the results. The colored features are the GIS system components and the black lines represent linework in DistributionSys. The black vertical busses line up with the red nodes, thus verifying the employed scaling procedure. The conductors do not match because their locations were drawn by DistributionSys according to their topological connection between nodes. This is handled in GIS by assigning coordinates to each vertex in the polyline. DistributionSys only provides for coordinates in the node attribution but could possibly be modified to mimic the GIS methods for mapping linework.

![Figure 5.8: Georeferencing verification results](image-url)
Chapter 6 – Conclusions

Through this effort, it is obvious that the integration of GIS and power system analysis efforts provides added functionality to the management of utility systems. As competition increases and as information technologies advance, a utility’s data becomes more and more valuable as a corporate resource. As a result, sharing information becomes very important to the efficiency of an organization. Though this research documents a small-scale integration, it highlights the ability of GIS to initiate full integration of electric utility information. The technique of integration and the role of GIS within the envelope of the entire information system can take many forms. However, through this research it is apparent that on a basic level, incorporating a spatial component to power systems analysis extends the capability into new areas.

More specifically, the integration with DistributionSys could be easily coordinated by the creators of the software. Since DistributionSys is currently utilizing tabular data storage for the entire model, it would be possible to coordinate the database with GIS to extend the capability of the software. In its simplest form, DistributionSys could utilize Microsoft Access for its primary template and its reporting mechanism. This simple step could greatly enhance the capabilities of the tool. Chapter Seven will further detail suggestions for future work.
Chapter 7 – Suggestions for Future Work

Because it is built upon a relational database structure and because of its ability to freely import and export tabular information, DistributionSys could be easily extended to interface more efficiently with Geographic Information Systems. At this point in the evolution of GIS software, the Access database (.mdb) is the foundation for the personal geodatabase. For smaller GIS applications or for further academic exercises, the formatting and reporting capabilities could be coordinated between the personal geodatabase and the DistributionSys network. This could produce automated transfers of information from one model to the other. The research documented in this paper demonstrates the basic interoperability and was accomplished manually with minor re-formatting.

Work could be extended to enable GIS as the Graphical User Interface into the network analysis capabilities of an engineering software package such as DistributionSys. The GIS could be the main reporting mechanism for DistributionSys. In the optimal situation, both software packages would be utilized to their respective strengths. For example, the mathematical analysis required for load-flow iterations, short-circuit potential, and voltage drop calculations could easily be performed in the background by DistributionSys and the system information required as input for these analyses could be housed in a database structure accessible to both GIS and to DistributionSys. The reporting could be delivered through the GIS map interface for both tabular and spatial information.

The main objective through an automated integration would be to allow comparison of DistributionSys data to other, seemingly unrelated systems. For example, once the automated integration is possible, a user may be able to ask questions such as:

*What is the optimum placement in the distribution system for distributed generation based on electrical parameters and based on proximity to existing fuel infrastructure [2]? *
*What would be the best place to expand the system both electrically and based on existing land-use or zoning restrictions? *
*Where is the optimum placement for a pad-mounted capacitor bank, based on necessary voltage support and existing road infrastructure (for delivery)? *
*Where is the nearest telecommunication hub for monitoring and control of remote switchgear, protective devices, or generators? *
The integration between GIS and engineering software packages could provide valuable scenario modeling for limitless applications.

In addition, this research identified a minor need for modeling three phase configurations with commercial, off-the-shelf GIS. This could be created as an open-source tool written in Visual Basic to extend the capabilities of GIS.

Finally, work could be undertaken to model the IEEE Feeders in GIS utilizing different data models such as SDSFIE, ESRI, or the IEC Common Information Model. A comparison of the data standards could provide valuable insight into the differences between the various system models.
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Vita

Philip Smith is a native of the Eastern Shore of Virginia. In May 2000, he received his Bachelor’s degree in Environmental Science from Virginia Tech with a focus on water resources. Upon graduation, he went to work for the University of Virginia (UVA) in support of a National Science Foundation, Long-Term Ecological Research center in Oyster on the Eastern Shore. He worked for UVA for two and a half years as a marine scientist supporting GPS surveying, GIS analysis, and boat operations throughout the Virginia Coast Reserve. In February 2003, Philip began working for the National Aeronautics and Space Administration (NASA) under a cooperative agreement for the Facilities Management Branch at Wallops Flight Facility. Through this arrangement, he worked as an engineer at Wallops and undertook a Master’s of Science in power systems at Virginia Tech. Alternating periods of study and work with NASA, Philip transitioned into his role as an engineering project manager, electrical distribution system co-owner, GIS Team Leader, and assistant energy manager for Wallops’ Facilities Management Branch. He conducted his Master’s work under the direct supervision of Dr. Jaime De La Ree and with the guidance of Dr. Virgilio Centeno and Dr. Yilu Liu. Philip Smith completed his M.S. in Electrical Engineering in December 2005 and immediately converted to work as a civil-servant project manager at Wallops Flight Facility.