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MAPPING THE ELECTRICAL INFLUENCE OF DISTRIBUTED GENERATION ON RADIAL DISTRIBUTION NETWORKS USING GEOGRAPHIC INFORMATION SYSTEMS

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Introduction

Current restructuring of the electric utility industry has aroused vast interest in emerging distributed generation (DG) technologies. Some of the most obvious benefits of DG include, but are not limited to the following [1]: a) Emergency backup during sustained utility outages, b) Value of energy savings through peak shaving, and other rate-reducing means, c) Reduced voltage sags, c) Increased reliability, d) Potential utility capacity addition deferrals. But in addition to providing many benefits to the electrical power infrastructure, the incorporation of DG affects traditional over-current protection schemes by introducing reverse power flows (Figure 1).

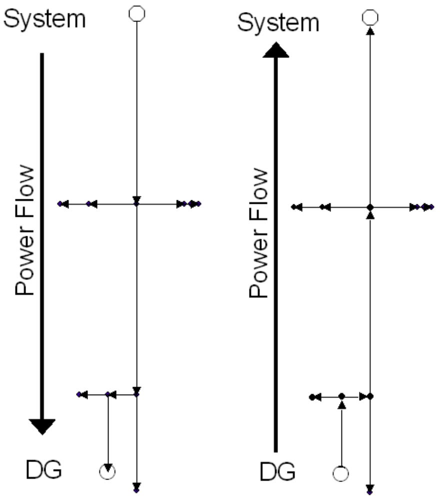


Figure 1: *Power flow in two directions*

The fault current contribution from a distributed generator could cause an unnecessary trip of a protective device and incorrectly disconnect a healthy load [2]. Therefore, in planning for the addition of DG to a radial distribution network, it is important to identify those pieces of equipment and protective devices that are close enough in the network to be electrically affected by the DG fault current. If a fault occurs beyond a certain electrical distance (in ohms) away from the DG, its contribution to the fault current is minimal since it is limited by the series impedance of all conductors and equipment in the path. This paper provides a method, utilizing Geographic Information Systems (GIS), for selecting a section of a radial distribution network based on the magnitude of the impedance away from any system generator.

Geographic Information Systems

Geographic Information Systems are widely utilized in a vast array of industries for the purposes of mapping, analyzing, organizing, and graphically interfacing all types of data. The foundation of a GIS is rooted in conventional database structure. However, unlike traditional databases, GIS maintains spatial attributes for all data. Since every record in a GIS database has underlying coordinates, the data can mapped to its correct position on the earth’s surface and interfaced in a map format. Subsequently, traditional queries can be performed and new spatial relationships can be identified, all within a graphical map display.

Common power system GIS applications include site selection, marketing, outage management, and in some cases, operations or system engineering. The intent of this paper is to utilize this emerging technology as an engineering or planning tool to map electrical distance on purely radial distribution systems.

Raster/Vector GIS Network Models

Conventional GIS network applications utilize vector data by modelling the system using points, lines, and polygons. For example, a transportation GIS may contain line segments that portray street centrelines and points that represent road intersections. In such a case, each piece of the network has its own individual record in a database. Tools exist for modelling changing attributes along lines in a vector network. For example, linear referencing makes it possible to identify an event, such as a milepost on an interstate, by its distance from a starting point along the network line.

Though packaged analysis tools exist for vector networks, a raster (grid) approach was employed to allow use of Environmental Systems Research Institute’s Spatial Analyst. Raster data is pixelated, with each cell containing a value. Each cell can hold either floating point values or integers and “blanket” mathematical functions can be applied to every cell in a raster. Though Spatial Analyst is not structured for network analyses, it contains many powerful tools that can be creatively adapted to suit network needs [3].

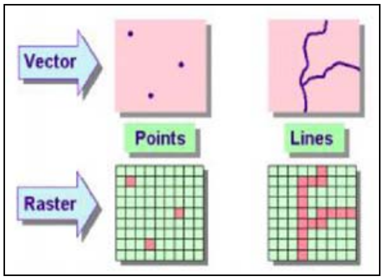


Figure 2: *Vector versus raster (grid) GIS datasets*

The fundamental idea of a raster network model was adapted from methods common to watershed delineation and flow accumulation in stream networks. “Stream burning” is the process of artificially lowering the elevation under a known stream location. By “burning” a stream into an elevation model, flow is forced into a known sink. This idea can be adapted to power distribution networks by artificially raising the impedance of cells off the network to extreme amounts in an effort to calculate impedances only along the network path.

Test System

The system used in this analysis is the 13-Bus Radial test-feeder [4] created by the IEEE Distribution Analysis Subcommittee as a test system for emerging computer applications (*see Figure 3*). The system operates at 4.16kV and contains seven different conductor configurations. The impedances of these configurations and their associated lengths are the driving inputs to mapping electrical distance in GIS. Using the characteristic impedance per length of a particular conductor coupled with its physical length, electrical distance in ohms can be inferred. From another perspective, the conductor impedance can be viewed as the weight, or travel cost along the network. In transportation networks, this travel cost would be a speed limit on a road. In either case, this impedance limits flow through the system.

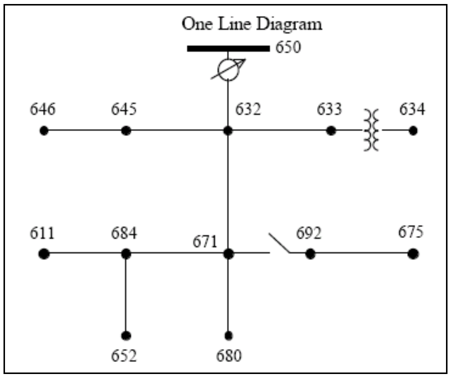
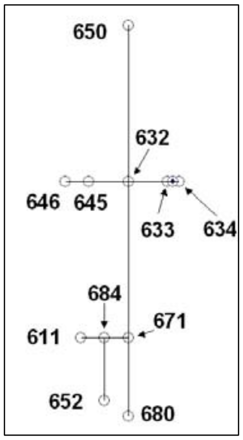


Figure 3: *13-Bus IEEE Radial Test Feeder*

Creating a GIS network model for 13-Bus system

The 13-Bus system was built in ArcGIS with proper scaling and with correct conductor lengths. It is important to recognize that data should be projected to ensure correct distance measurements. Like a paper map, GIS displays the spherical surface of the earth using a two dimensional medium. In the digital case, this medium is the computer screen. However, to accurately account for the curvature of the earth for precise distance measurements, it is necessary to project the two dimensional model onto a three dimensional surface. In this example, the projection used is State Plane Virginia South, measured from the 1983 North American Datum with map units of feet. In the case where a vector GIS system model is present, attention should be given to the pre-defined projection to ensure correct spatial measurements before proceeding. All nodes are snapped to correct vertices and line lengths.



With the network structure built, IEEE system data is added to the database records for each piece of equipment. Most importantly, the size of conductors and their configurations are added to the records for each line segment in an effort to identify characteristic impedance per length. This impedance can be found in cable specifications or in tables used for various distribution system software packages. In this study, resistance and reactance for each conductor configuration were extracted from “Fault Checker 3.01” [5]. Magnitude of the complex impedance is calculated and used throughout the analysis. The calculation for impedance magnitude is the known relationship:

$$\boxed{Z = \sqrt{R^2 + X^2}}$$

Converting Vector Model to Raster

Once the vector model is built correctly, with impedances per length for every conductor and correct spatial scaling, it can be converted to a raster dataset. Similar raster GIS methods were applied to electrical networks in analyzing the incremental cost to distribution networks by Monteiro et al. [6]. When converting to a raster, the cell size should be set to the “per unit length” of the impedance. For example, if a conductor has a characteristic impedance of 108 $\mu\Omega$ per foot, the cells of the raster should be set to one foot squares. As a result, the impedance across that individual cell would simply be 108 $\mu\Omega$. These cells setting make it possible to sum impedances along a network path and to translate physical distance to electrical distance.

Conductors should be converted with impedance per cell size as the value assigned to grid cells. Also, equipment such as transformers and generators should be converted with the same cell size and with equipment impedance as the grid value. Since all vector nodes were initially snapped to the lines, the cells representing nodes will occupy the same square foot as the final cell of the conductor. The impedance of these common cells can be added using the raster calculator or the conductor impedance can be neglected since it will be very small relative to that of a generator or transformer.

All cells not part of the network and within view should be assigned an impedance of 10,000 ohms per foot. This "artificial" large impedance will restrict any flow across the entire spatial extent to only those cells on the network [7].

Creating the Cost-Distance Raster for any System Bus

Using Spatial Analyst, a cost-weighted distance raster is created for the bus of interest. This tool will calculate the summed impedance along the path of least resistance to the bus of interest. Since the off-network cells were assigned very high impedances and since the source is always on the network, the path of least resistance from any point on the network back to the source can only be along network cells. This solution creatively restricts any current flow to the network. The final result is a map where each network cell represents the total impedance from that point to the bus of interest. This grid can be viewed as a map of electrical distance away from a generator.

The summed impedance grid can be queried and all cells containing impedance values below a certain limit can be extracted. These cells can be converted back to vector lines and mapped as impedance limits away from a certain point in the system. This step in the exercise is valuable for selecting the part of the radial distribution system that is within a certain impedance of a piece of equipment. For example, when adding a distributed generator, it is necessary to identify what part of the system will be electrically affected. There exists a limit in the system driven by impedance, beyond which DG will contribute only a negligible amount of fault current. Outside this boundary, or beyond this impedance along the radial network, the addition of distributed generation will have an insignificant influence under fault conditions. Once an impedance limit for a generator is calculated, it can be mapped and all equipment within its area of influence can be identified. In large, complex radial distribution systems, this can expedite the planning process by eliminating analyses of unnecessary equipment. Figure 4 shows different electrical distances away from the same distributed generator.

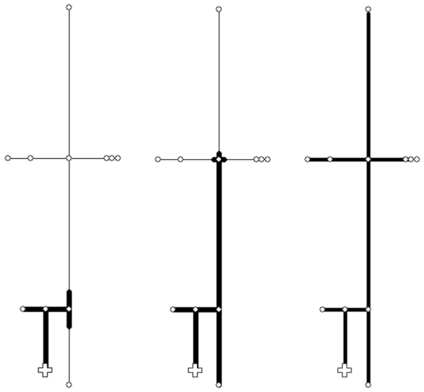


Figure 4: *9, 9.2, and 9.4Ω away from 2MVA DG*

Superposition of Short Circuit Currents

After the raster network is built and impedances are assigned to every linear foot of conductor and all equipment, electrical distances can be calculated quickly away from any point in the system. This is of particular interest when considering adding distributed generation to a system and creating power flow in two directions.

Once the summed impedance grid is created away from a generator, it can easily be transformed into a short circuit model by multiplying its inverse by the system voltage using the Raster Calculator. The cells of the resulting grid contain the short circuit contributions from the generator to a fault at any given cell in the model.

A short circuit grid is created relative to only one particular generator. To account for power flow in two directions, it is necessary to create a short circuit grid relative to the system and one relative to the distributed generator. Once a short-circuit raster has been created relative to every system generator they can be summed using the principle of superposition (as illustrated in Figure 5). The cells of the resulting model possess the total short-circuit current values for every point on the network, which contain the fault current contributions from every system generator. From this information, it is then possible to identify segments of the network that would need changes in protection settings with the addition of DG.

Further Applications and Conclusions

This methodology provides the framework for a raster GIS application to power systems and the addition of DG. At this point, it is necessary to realize that the application of this mapping software is not intended as a strong circuit analysis tool, but more as a graphical display that provides a dynamic "bird's eye view" of an entire distribution system and a simple approach to approximate the effect of DG. Further study could be pursued to apply the grid principles presented in this article to a vector model.

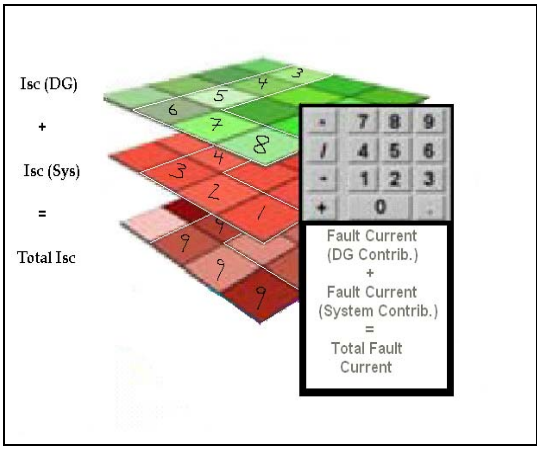


Figure 5: *Superposition of grids*

Since most networks are modelled as vector, this would open many other analysis capabilities inherent in the basic GIS functionality. For instance, protective devices could be modelled as points on the network and their settings could be maintained and/or changed with relative ease. The major obstacle involved would come in applying continuous values along linear network segments. For example, in the raster format, each cell can possess a different value (summed impedance, fault current, etc.), whereas a vector line only maintains attributes for the entire segment. Linear referencing and dynamic segmentation are two possible prospects which allow data values to be assigned at certain distances along a vector line. These processes are commonly utilized in transportation GIS for mileposts and in logistical GIS applications for addressing buildings. In addition to vector modelling, these methods could be extended to looped networks through further research. The methodology provided in this paper applies to purely radial systems and does not extend to consider the summation of parallel impedances.

This article proposes a creative solution to an emerging need in power systems engineering by utilizing and applying common geographic information system tools. When analyzing large systems such as electrical distribution networks, it is important to focus all resources on the task at hand. In the case of adding DG, part of the network will be unaffected electrically by the addition of such a device. This portion of the system can be excluded from the engineering analysis and attention can focused on the protection settings within the affected area.

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