Method for Developing Power Distribution System Case Studies Using Land Use Zones

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Abstract—**Data for power transmission systems is often very easy to find for many countries throughout the world. However, this is typically not true for systems at the power distribution level. This work introduces a method for creating synthetic distribution grids that can be used by researchers to develop power system case studies for any arbitrary area. The algorithm for creating these grids is implemented by first calculating the power consumptions of zones within the area of interest based on their designated land use. Then, distribution substations are systematically placed within these zones and connected to one another with power lines.**

Index Terms—**Land use zones, power distribution, resilience, synthetic model**

I. Introduction

Developing power system case studies is critical for continued research in improving the resilience of these networks. Case studies allow researchers to better understand how real-world power systems operate and how they respond to different situations. By examining simulated power system operations and disturbances, important findings can be identified, such as challenges that power system operators will face, factors that affect system performance, and strategies that can be used to improve resilience.

Two components of power grids that are useful for case studies are the transmission and distribution systems. The transmission system is used for transporting power over long distances at a very high voltage from power plants or other generation facilities to distribution system substations. These substations step the voltage down to a lower level, and then the power is distributed to the surrounding loads, such as homes and businesses. Data for transmission systems is typically accessible for many countries throughout the world [1]-[3]. However, the opposite seems to be true for distribution level systems. While governments typically have data for these networks, the information is not widely available to the public due to security and confidentiality policies [4]. Because of this, researchers who wish to develop case studies for and analyze impacts on distribution grids would likely have to develop their own synthetic models, which can be a complicated and time-consuming task that must be completed in addition to the primary efforts of their research.

Many methods for developing synthetic distribution networks have been introduced into the literature [5]-[8]. In each of these, the placement of the power lines were based on available road infrastructure data while the amount and locations of substations were determined using different approaches. This work proposes a relatively simple and effective algorithm that can be used to develop synthetic power distribution grids for cities that can serve as the bases for case studies. As opposed to the strategies in [5]-[8], the proposed method incorporates land use data to estimate the power consumption of areas throughout a city to determine the amount and locations of substations within a given area.

Land use is the term used to describe the economic or cultural activities of a certain area [9]. It is officially assigned to a particular location by government agencies through land surveys, and these often dictate certain rules that must be followed for anything constructed in the areas. Each type of land use zone has an accompanying zone function, which is the activity that people will primarily do within the zone. There are many different broad categories of land use, such as recreational, agricultural, and residential, and one important step in developing distribution system grids is to estimate values for the power consumption of these zones. Because this work is focused on developing systems for cities, residential and commercial zones are considered, while zones associated with rural areas, such as agricultural zones, are not.

Land use data for a multitude of countries is publicly available. One very common source, and the one used as a reference when preparing the case study in this work, is the OpenStreetMap database [10]. This contains a dedicated dataset for land use, and maps prepared with this data can be easily used with the proposed algorithm.

II. Power Consumption of Land Use Zones

Several methods for estimating the power consumption of cities have been proposed [11], [12]. The exact methodologies between these differ, but they all use publicly available information and tend to be approximations based on the best available sources of data. The approach used in this work is a novel way of calculating power consumption; a typical power density, in watts per square meter, was determined for each different land use zone type based on publicly available data for these areas. The specific methods and data used to obtain these densities are discussed below.

The land use zone types considered in this work are

1) *Suburban Residential Zone (SRZ)*: consists primarily of people living within houses. The zone function is residing. In this work, the power density for this zone

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was estimated by examining some statistics for the average power consumption and area of a typical home. The power density value used was 0.23 watts per square meter.

2) *Business District Zone (BDZ)*: consists primarily of office buildings. The zone function is the provision of services, such as banking, education, health care, government administration, legal services, restaurants, and many others. The power density value used was 30 watts per square meter.
3) *Urban Residential Zone (URZ)*: consists of apartment buildings that have three or four floors. There are also many relatively small shops. The primary function is residing. The power density was estimated by assuming that the power consumption is the same as a residential home and by determining the average size of an apartment, the average number of floors in an apartment building, and the average number of apartments on a floor. The value used was 13.5 watts per square meter.
4) *Retail Zone (RZ)*: consists primarily of large-scale shops such as malls, superstores, and restaurants. The zone function is in-person commerce. The power density was estimated by determining the average power consumption of superstores and was 65 watts per square meter.
5) *Dense Urban Zone (DUZ)*: consists of a mix of apartment buildings with four or more floors, businesses, and small retail areas. Therefore, the function of this zone type is a combination of those from BDZs, URZs, and RZs. Because of this, the power density for this zone was considered to be a weighted average of the densities for those three zones. The density used was 22 watts per square meter.
6) *Industrial Zone (IZ)*: consists of industrial complexes or several manufacturing facilities. The zone function is manufacturing or producing goods or products. In general, the power consumption of industrial and manufacturing facilities can vary considerably with the type of industry [13]. Because of this, it is difficult to determine a single, specific value for the power density of an IZ. However, the consumption can be estimated by first determining the total power consumption of the city, P_c. This can be estimated by using publicly available data such as the power consumption per capita of a country and the population of the city of interest. The total power of all IZs can be obtained by subtracting the total power of all other zone types in the city, P_Z, from the consumption of the entire city. Assuming that the ratio of the power of an individual IZ, P_{IZi}, to the sum of all IZ powers is equal to the ratio of the area of the IZ, A_{IZi}, to the total area of all IZs, A_{IZt}, the density can be calculated as

$$P_{IZi} = \frac{A_{IZi}}{A_{IZt}}(P_c - P_Z) \tag{1}$$

where i indicates a specific IZ.

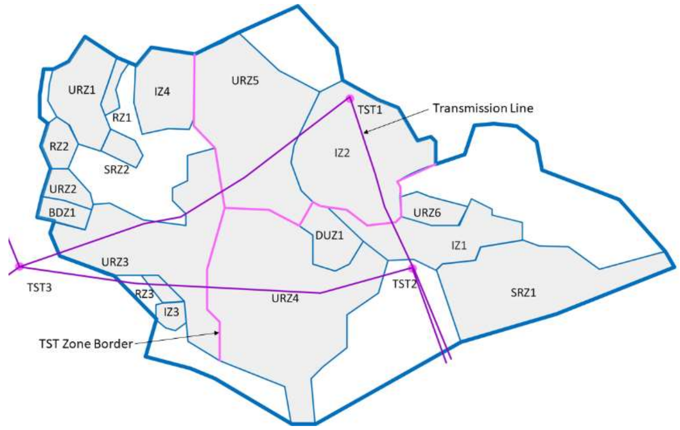

Figure 1. Land Use Zones and TSTs in City M

7) *Other Land Use Zone (OZ)*: consists of relatively open areas that require services for different reasons. These could be areas such as farms, mines, and tourist landscapes. The power consumption could vary considerably and should be determined similarly to IZs. OZs are typically not in cities and are therefore not included in the case study in this work.
8) *Empty Zone (EZ)*: consists of parks or other areas with little or no use of services. Therefore, these zones do not have a significant power consumption.

For the purposes of this work and to provide a general basis for discussion, actual infrastructure, population, and building information from real cities was applied to an imaginary city, called City M. A map of this city is shown in Figure 1. It consists of at least one of each type of land use zone except for OZs, where unlabeled zones are EZs that have a negligible power consumption. Power is delivered to City M through transmission lines that are connected to three transmission substations (TSTs.) The goal of this work is to illustrate a method that can be used to develop distribution networks that would extend from these TSTs to service the loads in the various zones.

After determining power densities for the zones in the city of interest, the area of each zone must be calculated. If a map, such as the one in Figure 1, is prepared, the areas can be easily determined by using geospatial software tools. However, using these areas to calculate power consumptions would be a significant overestimate of the actual consumptions due to the fact that a significant portion of a zone could be space where power is not being consumed. For example, a majority of the land in typical SRZs is yards surrounding homes as well as roads and some parks. The percentage of a zone's area that has power consuming loads will vary considerably between different zone types and different cities. Because of this, it is left to the user of the algorithm to determine an acceptable percentage based on available map and population data. When examining actual city maps, it was determined that between approximately 10 to 20 percent of land in most zone types is occupied by buildings. Because of this, for simplicity, it was assumed that 10 percent of the area of all zones in City M has power consumption. Table 1 is a summary of the power

Table 1: Power Consumptions of Zones in City M

Zone	Actual Area (km^2)	Power Consuming Area (km^2)	Consumption (MW)
SRZ1	2.53	0.253	0.058
SRZ2	0.69	0.069	0.016
BDZ1	0.47	0.047	1.41
URZ1	4.94	0.494	6.67
URZ2	1.61	0.161	2.17
URZ3	9.87	0.987	13.3
URZ4	12.0	1.20	16.2
URZ5	13.1	1.31	17.7
URZ6	1.18	0.118	1.59
DUZ1	2.05	0.205	4.51
RZ1	0.33	0.033	2.14
RZ2	0.99	0.099	6.44
RZ3	0.55	0.055	3.58
IZ1	5.20	-	38.9
IZ2	8.75	-	65.5
IZ3	0.98	-	7.34
IZ4	1.66	-	12.4

consumption values throughout City M. As noted previously, the consumptions of all zones other than the IZs were determined first, and these were used with (1) to calculate the values for the IZs. The total average power consumption of City M was assumed to be 200 megawatts.

III. Creating the Synthetic Grid

The land use calculations described in Section II are used as inputs for an algorithm that systematically places substations throughout a city map and then connects these substations to one another subject to several restrictions related to system standards and practices. The entire process can be divided into four subprocesses: preliminary steps for preparing the data, placing the substations, connecting the substations, and adjusting the connections. In general, many of the assumptions and values used while performing this process on City M were simplistic for the illustrative purposes of this work. However, users may easily implement more accurate values for their specific scenarios, assuming that these data are available for the cities under consideration.

A. Preliminary Steps

Before the algorithm can be implemented, several preliminary steps must be completed by the user. First, as detailed in Section II, a map of the land use zones and TSTs in the city of interest should be prepared, and the expected power consumptions of each zone should be calculated. Next, the user should determine which zones would be serviced by each TST and group them together into TST zones. The method used for this step could vary based on the city information known by the user, but, for this work, the groupings were determined based on proximity to the TST and an assumption that each of the three TSTs would have as close to a third of the total city demand as possible. Borders that indicate which zones were grouped within the TST zones can be seen in Figure 1. Substations within different TST zones will not be connected to one another.

Another important preliminary step is to set restrictions, assumptions, and ratings for several components in the synthetic grid based on typical values used in real power systems. For the distribution lines, the system voltages and ampacities should be selected. For simplicity, a single system voltage of 13.2 kilovolts was selected for City M. Two lines with different ampacities were selected as options that can be used when connecting substations. The first option has an ampacity of 1,300 amperes, and the second option has a smaller ampacity of 520 amperes [14]. Also, it is assumed that typical voltage compensation components would be included where necessary along all lines. For substation transformers, the power ratings should be specified. Because RZs and IZs tend to have a significantly higher power density than all other zone types, the distribution substation transformers for these zones were assumed to have a higher power rating than those in all other zones. The transformers were rated for 3.75 megavolt-amperes in RZs, 7.5 megavolt-amperes in IZs, and 2 megavolt-amperes in all other zones [15]. Also, it is assumed that the TST transformers would be properly sized for their expected loads. Finally, the power factors of the loads throughout the city should be specified. For this work, it was assumed that all loads for the lines placed in City M were wye-connected and had a power factor of 0.9 lagging.

B. Substation Placement

The placement of the distribution substations (DSTs) is accomplished through geometric analysis techniques. The algorithm for placing the DSTs consists of the following steps:

1) Calculate a first approximation of the required number of substations, N_i, in substation i. This is completed by dividing the total power consumption of each zone by the corresponding transformer power rating and rounding the result up to the nearest whole number.
2) Treat each zone as a polygon. Divide these polygons into N_i smaller polygons that have equal areas. For most cases, there may be multiple valid ways to evenly divide a zone into equal areas. However, any result should be sufficient for the purposes of this algorithm.
3) For each of the N_i polygons in a zone, determine the location of its centroid. Place a DST at each centroid and assign a number to each. If a TST is within the zone, this is treated as one of the required DSTs.
4) Determine the x- and y-coordinates, in units of length, of each DST, where the origin of coordinates is the TST corresponding to the DST. This step is not required to continue with the algorithm, but it is convenient for preparing maps based on the results.

As an example, Figure 2a shows the placement of the DSTs in IZ2. The power consumption of this zone, as shown in Table 1, was 65.5 megawatts. Dividing this by the 7.5 megavolt-ampere rating of the transformer, N_{IZ2} was determined to be 9. As shown in the figure, 8 DSTs were placed within the zone. The ninth required substation was

TST1 in accordance with step 3. Each of the 9 substations were assumed to provide one-ninth of the 65.5-megawatt demand for the zone, or about 7.3 megawatts.

C. Substation Connections

The next set of steps is a first attempt at connecting the DSTs to each other or to a TST. This is based solely on the proximity of one DST to another. The results of these steps may not be the final synthetic network; in most cases, the layout will have to be altered based on the line currents and their ampacities. The steps are

5) Start with a single TST zone. Determine which land use zones are closest to the TST. Connect a distribution line from the TST to the closest DST in these zones. This is the start of a run, which is a distribution line path that can be traced back to a TST.
6) Consider that one of the DSTs from the previous step is called DST-A. Determine the next nearest DST to DST-A that is not yet connected to a line. Call this DST-B. Also, determine the nearest substation to DST-B, and call this DST-C. If DST-C has not yet been connected to a line, then connect DST-A to DST-B. If DST-C has been previously connected to a line, then connect DST-B to DST-C.

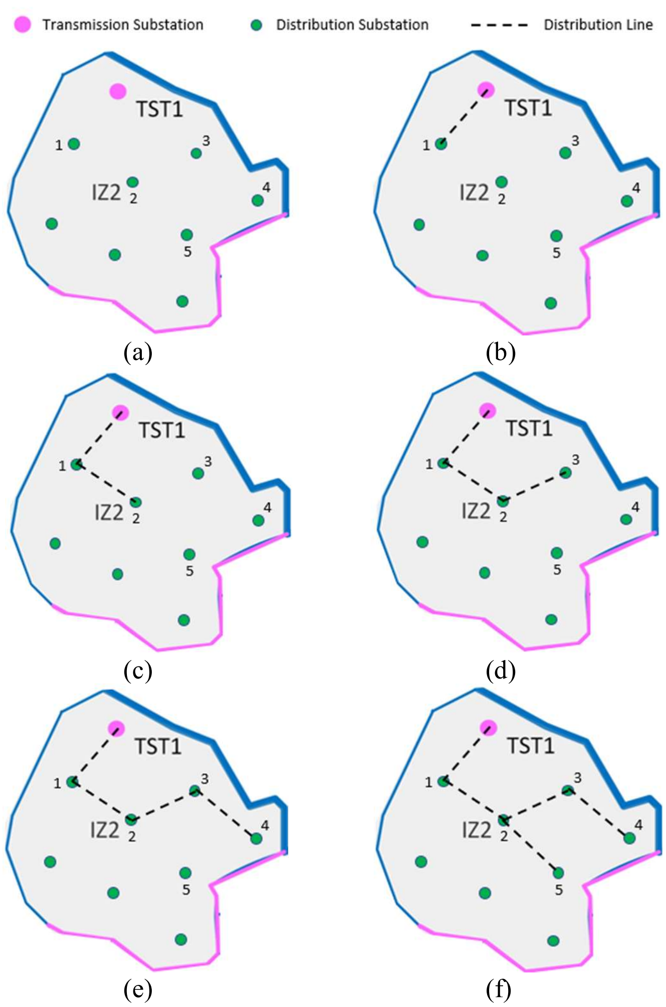

Figure 2. Placing the First Five Lines in IZ2

7) Repeat the previous step until all DSTs have been connected to lines, alternating between each run that was started in step 5.
8) Repeat these steps for the remaining TST zones.

The process for connecting the first five lines in IZ2 is highlighted in Figure 2. Figure 2b shows the initial connection from TST1 to the nearest substation, which is DST1. This is repeated in Figures 2c, 2d, and 2e, where DSTs 2, 3, and 4 are added to the run due to their proximity to the previously added DST. Note that, in Figure 2f, DST5 was connected to DST2 instead of DST4. This occurred because the nearest substation to DST5 is DST2 even though DST4's nearest substation, without a previous connection, is DST5. This ends the initial run and starts a new one.

D. Connection Adjustments

The previous distribution connection steps did not account for the power consumption of the zones and the available ampacities for the lines. These factors limit the number of DSTs that can be included in a single run. Because of this, each run that was previously established must be checked to ensure that the power demand is within the limits of the lines. If the limits are exceeded, then the network must be altered. The steps to accomplish this are

9) Starting with the lines coming from the TST, calculate the line currents using the relationship between three-phase voltage, current, and power [14]:

$$I_L = \frac{\sum_{\beta} P_j}{\sqrt{3} V_L \cos(\theta)} \tag{2}$$

where I_L is the line current, V_L is the line voltage, $\cos(\theta)$ is the power factor, β is the subset of all DSTs that are in the run, and P_j is the power consumption of a DST, j, in β.

10) If the current is less than the lowest ampacity value that was selected by the user during the preliminary steps, then the line is assigned that ampacity. If the current is greater than the lowest ampacity but less than the next largest ampacity, then the line is assigned the higher ampacity. This condition is checked for each ampacity option until one is selected. If the current exceeds the highest ampacity value, then an additional run will be established that branches from the substation. This will reroute some of the current from the original run through the second run, which may prevent the ampacities from being exceeded. This second run will connect the substation to the second closest DST. Any existing lines that connect the runs to one another are deleted. If the current through one of the lines is still too large, then additional branching runs will be added until the current levels are below the highest ampacity. In some cases, to keep the synthetic grid as realistic as possible, a line length limit is imposed on these additional runs so that excessively long, unrealistic lines are avoided. If an additional line in a branching run is ever going to be more than double the length of the line from the original

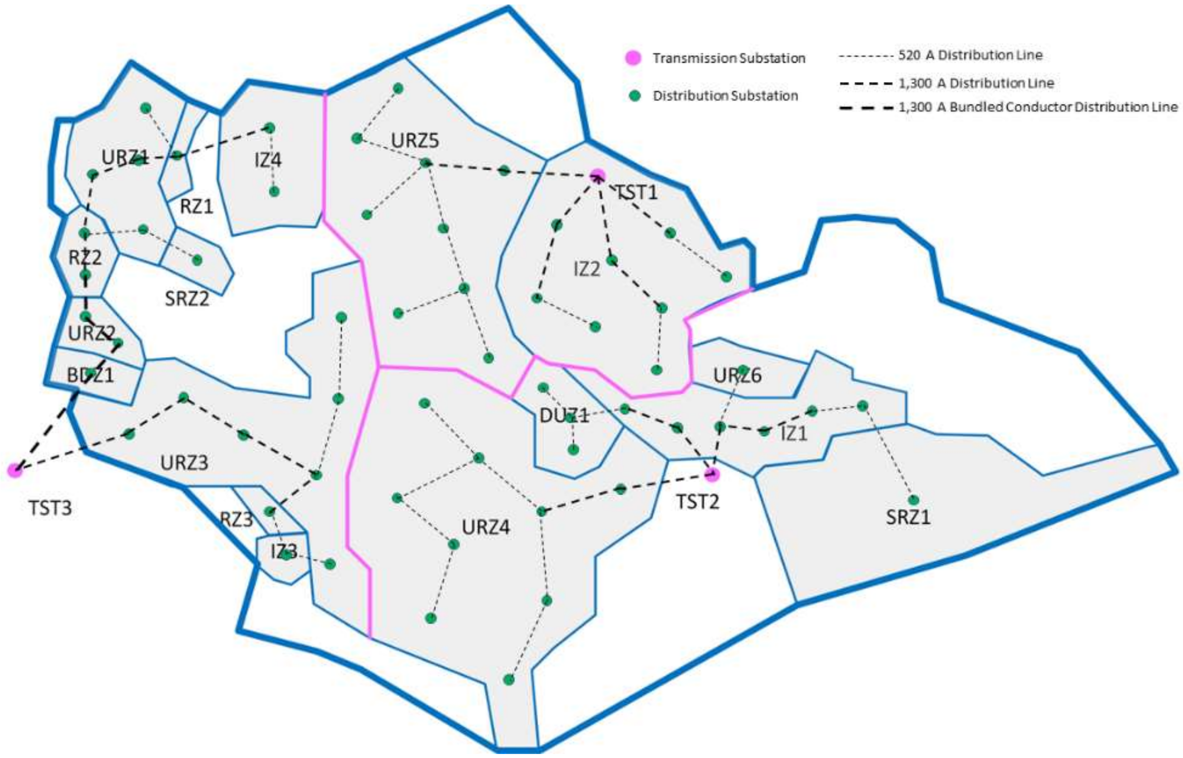

Figure 3. Synthetic Grid for City M

run, then it will not be used. Instead, a line with bundled conductors will be used in place of the original line because they allow for a higher overall current-carrying capacity [14].

11) Repeat steps 9 and 10 for all of the other lines.

The results of the entire algorithm for City M are shown in Figure 3. Note that the grid layout of IZ2 in this figure is very different from that shown in Figure 2f due to steps 9 to 11. Because the power consumption in the zone is very large, the initial run was divided into three runs in accordance with step 10. Also, lines connecting these runs, such as the line that connected DSTs 1 and 2 in Figure 2f, were removed. Finally, note that lines with bundled conductors had to be used in BDZ1, URZ2, and RZ2.

IV. FUTURE WORK AND CONCLUSION

The algorithm discussed throughout this work was used to systematically create a power distribution grid for City M. The authors would like to adapt the steps discussed in Section III into a single computer program that can perform all necessary calculations and generate maps similar to the one shown in Figure 3. Additionally, the resulting maps will be used for resilience studies of actual cities throughout the world. For most disasters, the most significant damage to the power system is at the distribution level [16]. Therefore, the algorithm presented in this work provides tools for studying those effects by simulating damage to the resulting synthetic grids. Finally, the authors will study the effects that machine learning strategies could have on some of the steps of the algorithm. For example, machine learning could possibly be used to connect the DSTs to one another in a more organized and robust way and could potentially reduce the number of runs that must be adjusted due to excessive line currents.

Because power transmission system data is much more accessible than distribution system data, researchers may have a more difficult time modelling distribution systems than they would for transmission systems. The algorithm developed for this work was intended as a useful tool for these researchers in developing power system case studies, and it only requires publicly available land use data to estimate the power consumption throughout an area of interest. Additionally, there is flexibility in the values that certain parameters can have, and this allows for the algorithm to produce useful and realistic results because users can choose values based on the practices and standards of the country and power system operators of the area of interest.

The algorithm consists of four subprocesses. The first is calculating power consumptions using land use zone data and selecting system voltage, line ampacity, and transformer power values. The second is placing DSTs throughout the land use zones based on the transformer power ratings and the geometry of the zones. Then, the substations are connected to one another through distribution lines based on their proximity to one another. Finally, the connections are adjusted, and the ampacities of the lines are assigned based on line current calculations with (2). As shown in Figure 3, the algorithm successfully created a synthetic grid for City M, which can easily be used as a basis for a power system case study for the area.

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