A Methodology for Electrical Energy Forecast and its Spatial Allocation over Developing Boroughs


Abstract -- Spatial load forecasting is not an accurate subject, yet it is important for the future safe operation of a distribution system. In this paper, a methodology for spatial load forecasting based on the combination of aerial images with statically procedures applicable to developing boroughs, is presented. The core of the study underlies in the adjustment and construction of the S-curves of both saturated and non-saturated small areas. The proposed methodology is validated through the energy forecast and its spatial allocation over a pilot borough.

Index Terms -- Energy, Load forecast, S-curve, Small area, Spatial allocation.

I. INTRODUCTION

One of the aims of a distribution company is to offer a high-quality service to its customers well-matched with its financial operation. An adequate planning of the distribution system requires the availability of the respective medium or long-run energy or demand forecasts. Commonly, long-term forecasts include some explanatory variables as regressors (e.g. GDP, demographic growth, evolution of residential, commercial and industrial customers, etc).

From the distribution planning standpoint the values foreseen for each year will need to be distributed onto the small areas created upon the geoelectrical area. Ideally, the whole forecasting process should be realized in an automated and integrated way. With a system like this, the distribution company will have a tool for the investment orientation useful for the maintenance and expansion of its network for both medium and long-term periods.

The lack of an adequate planning, thus the necessary investment and system expansion, will jeopardize the supply of energy which in turn will bring high penalties imposed by the regulator organ. Conversely, unnecessary investments on the system expansion will affect the company’s budget. A proper spatial load forecast will allow the company to foresee, well in advance, the possible trend and needs of the growing network, namely: distribution transformers, feeders and other network components.

Some of the references found make uses of GIS (Geographical Information System) as the assisting tool for load or energy allocation. The method used here uses also aerial images combined with trend and statistical methods.

Land-use based spatial load forecasting simulations provide very satisfactory results compared to statistically allocated load methods [1], hence the small area land-use approach presented here.

In recent years various methods directed to the spatial load forecast have been presented. References [1], [2] and [10], for example, present some techniques that can exploit the speed of modern computers when used for the referred purpose. Land-use based forecast methods, trending techniques, non-analytic methods and the load growth behavior are discussed in those methods. In [3] the results of a project to improve the extrapolation of distribution load growth are presented. Characteristic load growth curves for small area and feeder loading are also analyzed. References [4], [5] and [6] present applications of the fuzzy system theory over the spatial load forecasting. In particular [5] uses a set of preferential factors (i.e. distance to highways, to urban poles, etc) for developing the spatial load forecast. References [5] and [7] also address the problem of spatial load forecasting by introducing the urban re-development method.

Some other forecasting tools such as ANN (Artificial Neural Networks) and wavelet theory [8], [9], [10], Expert Systems [11] and Knowledge Discovery in Database (KDD) [12], aimed to land use in distribution systems were also proposed. An alternative approach, based on a piece-wise linear model for analyzing the evolution of the S curve upon a practical distribution system is presented in [13].

However, due to its inherent nature and despite all the efforts and modern tool available, spatial load forecasting is not an accurate subject. Thus, it is difficult to establish a ruling methodology applicable to each single problem. Each case has to be analyzed and tackled through a particular method or using a combination of methods.

As stated by [1]-[3], the load growth of a small area can be best represented through its S-curve (Fig. 1). A characteristic S-curve has three main parts [13]. The dormant or initial period that accounts for about 10% of the growth. The ramp period, that accounts for nearly 80% of the growth and finally the saturation period, which accounts for the remaining 10% growth.
II. DEVELOPED METHODOLOGY

A developing borough located at the SE Brazilian region was chosen as the pilot borough upon which will be tested the proposed methodology. It is foreseen that once validated this methodology, it will be used to spatially forecast the rest of the boroughs within the area of concession of the distribution company. Figure 2 shows the geoelectric map (small areas) of the pilot borough in 2005. All the consumption classes (residential, industrial, commercial, rural and public service) are included in this map.

The red square cells shown in Fig. 2 have the highest energy consumption followed by the orange ones, the yellows ones, the blue ones and finally the light blue ones which are in the lowest energy consumption rank.

Briefly, the developed methodology for spatial load forecasting used in the project is presented next:

a. Energy forecast per consumption class of the borough:
This first stage of the study is done regarding the 6-year consumption data (2000-2005) available as well as the respective explanatory variables. The long-term horizon forecasted was 5 years (2006-2010). Fig. 3 shows the data record period \((n-3, n-2, ..., n)\) as well as the forecast period \((n+1, n+2, n+3, ...)\) of a general forecast curve representing any class of consumption. The incremental energy of the first year of forecast is represented through \(\Delta E_{n+1}\).

b. Creation of small areas: The geoelectrical map of our pilot town was divided into square-cells (500 x 500m). Each small area, identified through a number, will provide information such as: its location, monthly and yearly consumed energy per consumption class as well as the percentage of the energy consumed by them. Likewise, it will provide information (kWh and location) of each single consumer.

c. Identification of the saturated small areas: This is accomplished using aerial images. These images also allow estimating the approximate percentage occupied by certain consumption classes (or sub-classes), namely: industrial areas, buildings, residential and rural areas. As each small area has an identifying number, the saturation threshold energy of these classes and their maximum energy \((E_{max})\) can also be obtained.

d. Treatment of non-saturated small areas: By the same token, non-saturated small areas will also allow identifying the main consumption classes within them. Furthermore, they will provide information of the available areas and restricted areas such as parks, rivers, highways, etc. As they grow resembling to a certain saturated small area, their maximum energy can be pre-defined based on the maximum energy computed for the saturated small area.

e. Obtention of the S-curve: Because the 5-year record of the energy consumption (kWh) is not enough to draw the S-curve of the saturated and non-saturated small areas, the following procedure and assumptions were made:

- Saturated small areas: Once computed \(E_{max}\) and having the 5-year record of energy consumption, a statistical procedure to complete and adjust the S-curve, using (1) which rules the load growth of a small-area [1]-[3], [14], was used.

\[
E(t) = E_{max} \left[ 1 - e^{\left(\frac{t-t_0}{\tau}\right)^2} \right] \tag{1}
\]

where:

\(E_{max}\): Maximum or saturation energy (load) in the small-area
\(t_0\): Initial growing time
\(\tau\): Time constant of the S-curve

- Non-saturated small areas: They will basically follow the S-curve growing pattern of the saturated (mother)
small areas. Possible prohibited areas inside these small areas will have to be subtracted from the available area. Thus, the reduced available area will be proportionally reallocated onto each class of consumption.

f. Spatial load (energy) allocation: Once obtained the S-curve of both saturated and non-saturated small areas, this step will allocate spatially the forecast energy previously calculated. For year \( n+1 \) (Fig. 3), for example, all the energy increments \( \sum_{i=1}^{m} \Delta E_{QUADS.i} \) of the small areas (per class of consumption) will be compared to the forecast energy calculated in (a), according to the following conditions:

i) if \( \sum_{i=1}^{m} \Delta E_{QUADS.i} \equiv \) forecasted energy (\( \Delta E_{n+1} \)), it means that \( \Delta E_{n+1} \) was thoroughly allocated; thus, we start dealing with the next annual increment of energy (i.e. the energy forecast in year \( n+2 \)).

ii) if \( \sum_{i=1}^{m} \Delta E_{QUADS.i} < \) forecasted energy (\( \Delta E_{n+1} \)), the presented methodology proposes to allocate the remaining energy (i.e. the difference of \( \Delta E_{n+1} - \sum_{i=1}^{m} \Delta E_{QUADS.i} \)) into new small areas.

iii) if \( \sum_{i=1}^{m} \Delta E_{QUADS.i} > \) forecasted \( \Delta E_{n+1} \), then the exceeding energy \( \left( \sum_{i=1}^{m} \Delta E_{QUADS.i} - \Delta E_{n+1} \right) \) will be reduced proportionally in all the small areas. This procedure is done until condition (i) is reached.

In the above equations, the term \( m \) stands for the number of small areas (excluding the saturated ones) existing in any of the consumption classes considered.

The new (empty) small areas created will adopt the S-curve and the time constant of the nearest neighboring small area. Because there may be more than one potentially influencing small areas, the nearest neighboring small area will chosen regarding a Merit Index (\( MI \)). The merit index will be calculated based on the following criteria:

- The eight small areas around the new one (candidate) are firstly selected.
- Next, the ratio between the total energy of the last year, in the data record, to the \( E_{max} \) of each neighboring small area is then calculated.
- Finally, the mean value of the above ratios (obtained for each neighboring small area), will be the \( MI \) of the new (empty) small area.

The merit index of various new small areas area calculated and arranged in descendent order. The new small area with the highest merit index will be chosen and so forth, until no remaining energy is left. The new small area will adopt the S-curve of the most charged small area in the vicinity (eight neighboring small area).

A general block diagram of the above methodology is shown in Fig. 4.

III. RESULTS

In this section, a base case test showing the main results obtained with the proposed methodology will be presented. These results correspond to the pilot borough introduced in Section II. The long-term energy forecast of the commercial consumption class, for example, regarding the explanatory variables (local GDP and residential energy consumption) is shown in Fig. 5. Three scenarios of forecast (optimist, conservative and regular) were calculated in each forecast. The “regular” energy forecast depicted in Fig. 5 will be allocated in the small areas.

![Fig. 5. Energy forecast (2000-2010) for the Commercial consumption class](image-url)
In Table 1 the annual increment of the forecasted energy corresponding to the Commercial consumption class, which was shown in Fig. 5, is presented.

<table>
<thead>
<tr>
<th>Year</th>
<th>Forecast Commercial increment MWh</th>
<th>Annual increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>38949</td>
<td>--</td>
</tr>
<tr>
<td>2006</td>
<td>40629</td>
<td>1680</td>
</tr>
<tr>
<td>2007</td>
<td>43301</td>
<td>2672</td>
</tr>
<tr>
<td>2008</td>
<td>46180</td>
<td>2879</td>
</tr>
<tr>
<td>2009</td>
<td>49281</td>
<td>3101</td>
</tr>
<tr>
<td>2010</td>
<td>52622</td>
<td>3341</td>
</tr>
</tbody>
</table>

From Table I, the energy increment in 2006 is equal to \( \Delta E_{2006} = 1680 \) MWh. This energy must be allocated in both developing and new small areas within the geoelectric map. On the other hand, the energy allocated over all the developing small areas (as they have already defined their growing rate) was equal to \( \sum_{i=1}^{N} \Delta E_{QUADS,i} = 1190 \) MWh, thus, the difference (1680-1190) = 490 MWh will need to be allocated in new small areas. Next, an example showing the way the MI should be calculated is presented. To do so, a small part of the commercial class in the geoelectric map (pilot borough) was chosen. The small areas Q2864, Q2865, Q2866, Q2942 and Q3020 (Fig. 6) were already occupied in 2005, whereas Q2943, Q2944, Q3021 and Q3022 were empty.

The respective maximum energies of Q2864, Q2865, Q2866, Q2942 and Q3020 as well as their MWh in 2005 are shown in Table II. Obviously, the ratio \( \frac{E_{2005}}{E_{\text{max}}} \) for Q2944, Q3021 and Q3022 is zero.

<table>
<thead>
<tr>
<th>Small area</th>
<th>Energy in 2005 (MWh)</th>
<th>( E_{\text{max}} ) (MWh)</th>
<th>Ratio ( \frac{E_{2005}}{E_{\text{max}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2864</td>
<td>415</td>
<td>1200</td>
<td>0.3458</td>
</tr>
<tr>
<td>Q2865</td>
<td>1189</td>
<td>1500</td>
<td>0.7927</td>
</tr>
<tr>
<td>Q2866</td>
<td>615</td>
<td>1200</td>
<td>0.5125</td>
</tr>
<tr>
<td>Q2942</td>
<td>335</td>
<td>1000</td>
<td>0.3350</td>
</tr>
<tr>
<td>Q3020</td>
<td>380</td>
<td>980</td>
<td>0.3877</td>
</tr>
</tbody>
</table>

The MI for each empty small area (Q2943, Q2944, Q3021 and Q3022) is obtained through (2):

\[
MI_{Q2943} = \frac{\sum (\text{Ratio}_{Q2943})}{8} = (0.3458+0.7927+0.5125+0.3350+0.3877+0+0+0) = 0.2967
\]

It turns out that the MI of Q2943 (empty) presents the highest value compared to Q2944, Q3021 and Q3022, whose MI were similarly calculated. So, the small area Q2943 will have priority in receiving the remaining forecasted energy over Q2944, Q3021 and Q3022. In Fig. 7, a partial aerial image of the used region, upon which the small areas (500mx500m) were created, is presented. Note that unlike the case of some other urban regions or other big cities, it has a few, if any, high rise buildings. Thus, the energy (load) contained and handled in the small areas will be less compared to those of big cities. This also implies that both the residential and commercial classes will not need characterizing a sub-class featured by high rise buildings.

In Fig. 8, the spatial load growth of the pilot borough’s commercial class is shown. Notice the identification number given to each small area and the scattered pattern of some small areas within the map. The green-colored small areas represent the occupied area in 2005. The red color and yellow color small areas appeared in 2006 and 2007, respectively.

This same procedure was applied to the other consumption classes (residential, industrial, rural and public service). The energy allocation of the above consumption classes in 2006, served as an input for the energy allocation in 2007. The spatial allocation of these two years, mainly 2006, served to diagnose and validate the methodology presented. The preliminary results obtained showed to be good as they were accordant with the actual spatial growth of the analyzed pilot borough.

### IV. REMARKS AND DISCUSSIONS

It should be noted that all the consumer classes within a certain small area are in reality scattered and mixed up unevenly. Only for ease of analysis, it was considered that these consumption classes are evenly grouped as shown in Fig 9(a). Likewise, prohibited areas were grouped and calculated the percentage that they represent within a small area (Fig. 9b) this also facilitated the allocation process.
V. CONCLUSIONS

A methodology for spatial load forecasting based on the combination of aerial images with statically procedures applicable to developing boroughs, was in this paper presented. The combination of both land-use observations and statistical procedures enabled a better construction and adjustment of the S-curves of both saturated and non-saturated small areas. As presented in Section II(f), the forecasted energy per class of consumer obtained using the explanatory variables, served as the targeted energy to be attained while allocating the incremental energy in each small area.

The methodology proposed allows analyzing each small area individually creating S-curves for each consumption class within the small area. The saturated small areas are identified regarding the area occupied by the consumers (aerial image) and the total energy consumed in the last couple of years which was nearly constant.

The empty small areas were ranked through a merit index that shows the occupation trend of a certain area in relation to both the identification of the developing poles of a certain class of consumption and the time period needed to occupy such an area.

Finally, the methodology used upon the pilot borough showed itself consistent as it provided good results; thus, it could be used over some other developing boroughs.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

VIII. BIOGRAPHIES

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