SOLAR CITY : ASSESSING THE DETAILED EFFECT OF SOLAR TECHNOLOGIES ON ELECTRICITY NETWORK PERFORMANCE

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SUMMARY

Solar City is a project that aims to support designers of low voltage networks by modelling the effect of solar technologies used in urban areas. This paper describes the detailed load models, network analysis, software tool and test case that form the project output.

INTRODUCTION

Low voltage (LV) network designs based on heuristic approaches for estimating demand have so far worked well. As interest in renewable energy technologies increases, an understanding of the detailed impact of embedded generation on local demand and hence on LV networks becomes important. This in turn requires a better representation of the distributed load. Whilst considerable effort has been directed at modelling demand in the high and medium voltage areas of the distribution network, approaches to provide an accurate picture of distributed load within the LV networks are relatively sparse.

As well as a paucity of detailed load models there are few software tools available that support the design and development of the LV networks. The Solar City project aims to provide such support by linking fine-grained load models and a network analysis package within a software tool, SEnTIENT (Solar Energy Technology: Impact on Electricity Networks Tool). This paper describes the various elements of SEnTIENT in more detail but begins with a brief review of some of the modelling approaches that have been developed previously.

BACKGROUND

Most existing LV networks have been designed on the basis of empirical estimates of peak and average demands. Aggregated demands are calculated using a diversity factor. Research in New Zealand [1] revealed that there is a significant variation between the estimates used by different distribution network operators (DNOs) and generally such approaches can lead to over-engineered designs.

Another approach to estimate the scale or pattern of demand is time series analysis of measured data. For example, Bass [2] developed time series models to size wind generators for remote locations. The TESLA model [3] is widely used in the UK and adopts a time series approach, together with a variety of other analytical techniques, to estimate identifiable, latent, exceptional and unpredictable elements of the electrical demand. The Bass model provides half-hourly estimates suited to individual dwellings whilst the TESLA model is aimed at estimating peaks of aggregated demand over a supply region. Only a few modelling approaches, for example the work by Hyland and McQueen for domestic demand in New Zealand [1], provide continuous estimates of demand and account for diversity between connections. This is especially important to assess the detailed effect of solar technologies – identifying the duration and locations of voltage overloads in a local network clearly depend on it.

By adopting an end-use basis for demand models, such as for cooking, lighting, heating, cooling, etc., their application becomes more flexible. The models facilitate studies of changes in ownership, use patterns, efficiency and lifestyle – allowing demand patterns to remain realistic. In addition, relating components of the demand to particular appliance types allows a more accurate estimate of the active and reactive elements of the load. In the 1940s, Arvidson [4] examined a simple model that included nine different end-uses and provided a daily demand profile for each. Demand was derived from an hourly load that reflected occupancy behaviour and a basic profile that allowed for variation in the weather, built-form and building materials. Since then more complex models have become viable such as Bartel’s work in Australia [5] and Capasso’s research in Italy [6]. However, few models based on end-use are concerned with both demand and diversity.

The requirements for the Solar City load models are these:

- Load estimate per consumer connection point – for a realistic load distribution
- Coverage of both domestic and non-domestic (<100kW) demand
- End-use basis – to protect against future changes in demand patterns and to estimate power factors
• 1-minute average basis to capture spikes in the individual demand

Consequently, it was necessary to develop an alternative basis and methodology for the load models.

Sizing conductors in the LV networks has in the past, like load estimates, relied on considerable experience. Analysis tools that support network designs tended to specialise in primary distribution where decisions had far more impact on performance and capital cost. Tools for LV analysis must be suited to the multiplicity of nodes and radial nature of the network. Preliminary investigations under Solar City have shown that the Ladder Iterative Technique developed by Kersting is especially suited to this type of analysis [7]. A tool is being developed in MATLAB that performs an unbalanced three-phase power flow analysis. Early results on a 40-node network look promising.

A single feeder from a primary transformer can supply more than a thousand nodes and consequently some form of post-processing is required. Both the load models and the network analysis package for Solar City are linked by the SEnTIENT tool, which is described in the following section.

SEnTIENT – DESIGN CONCEPTS

The tool is based on dynamically linked relational database (MS Access) and Geographical Information System (GIS) technologies (MapInfo), allowing the LV network to be represented in a highly maintainable and user friendly way. Computationally intensive aspects of the work such as the demand and solar energy models are being implemented as object-oriented dynamic link libraries (DLLs) that can be called from both the database and GIS applications. The user may query both network detailed design (line lengths, conductor types, etc.) and performance (over-voltage, overheating, etc.) directly from the GIS.

The advantages of linking relational databases dynamically with a GIS are numerous. In this context, the user will be able to select a connection point in the library whilst simultaneously viewing the location on the map. Similarly the detailed demand profile for any connection point can be viewed in both ways. The tool will allow the user to adjust the underlying load model to simulate changes in the assumed profile of the network area to reflect different lifestyles or energy saving strategies.

The basic function of the GIS interface is to pull together the various strands of the package (figure 1), linking the various libraries, load model, network analysis package and an element known as ICUE [8], which estimates the solar yield from photo-voltaic (PV) or solar-thermal panels. ICUE facilitates the selection of appropriate sites for solar panels. This irradiation-mapping tool uses a 3D model of the network area, based on photogrammetry. The solar yield is estimated for both direct and diffuse radiation and produces a false-coloured contour image. This enables the user to define panel sizes to suit the location and to maximize the output. The estimated irradiation value for a panel is then used to predict the extent of exported supply (PV) or reduction in the modelled demand (solar thermal).

The network design can be readily modified and reports obtained on the associated performance factors such as peak and average voltages or duration of over-voltage. The tool will also highlight the location of problem areas in the network. Such features allow the user to quickly compare different design options in order to establish the best compromise.

SEnTIENT LOAD MODEL

All the end-use sub-models of the SEnTIENT load model are based on the same underlying methodology (figure 2).

The demand for domestic consumers is based on half-hourly averaged data. The daily profile for demand is highly non-linear due to the effects of occupant behaviour and the changes in the availability of solar heating and lighting. During the course of the day, demand varies due to the complex interplay of these factors.

For example (figure 3) a typical weekday profile for a domestic consumer shows low demand during the night with two peaks representing the demand at breakfast and during the evening. Demand during the day tends to be low because dwellings may be unoccupied and also because natural heat and light are available.
By analysing the annual instead of daily trends in demand, the variations due to occupant behaviour are reduced, especially if demand is analysed separately for different day types (weekdays, Saturdays, Sundays with special cases for public holidays). For the end-use demand, the annual trends can generally be expressed as the combination of a basic sinusoidal component, that represents the effect of solar heating or lighting, and a random element, that represents the variation in occupant behaviour and weather effects:

\[ D_{\text{end-use 1}} = s_{\text{end-use 1}} \sin(2\pi(N_d/366) - \phi_{\text{end-use 1}}) + k_{\text{end-use 1}} + r_{\text{end-use 1}} \]

where:
- \( D_{\text{end-use 1}} \) = half-hourly average demand (usually scaled by the annual peak demand)
- \( s_{\text{end-use 1}} \) = sine scale variable
- \( \phi_{\text{end-use 1}} \) = sine phase variable
- \( k_{\text{end-use 1}} \) = sine function constant
- \( r_{\text{end-use 1}} \) = random element of zero mean and given standard deviation, \( s\text{dev}_{\text{end-use 1}} \)
- \( N_d \) = day number (i.e. 1st January = 1)

To model lighting demand, it is necessary to use two sinusoidal components of different phase and amplitude. For many end-use demands there tends to be minimum and maximum cut-off levels to the demand in summer and winter.

The half-hourly demand is divided by the annual peak, such that the model provides non-dimensional trends that may be scaled to reflect year-on-year changes. The match between the modelled demand and measured data is generally good (figure 4, lighting demand for a typical domestic consumer, between 19.30-20.00)

For consumers with assigned ownership, the average half-hourly demand is scaled by a relevant factor, such as floor area or occupancy, to introduce a further realistic element of diversity. An appropriate appliance duty cycle is triggered randomly to provide 1-minute average demand such that the total in each half-hour is matched to the assigned value. The duration, frequency and scale of an individual demand event are varied randomly within specified bands. This provides a further element of diversity such that consumers who are assigned identical half-hourly demand will appear to have different 1-minute average demand profiles. For each end-use, the output will be 1-minute average demands with an associated power factor. By combining the various end-use demands, the total active and reactive components may be calculated for each individual node of the network.

The model is intended to include light non-domestic consumers, with a peak demand of less than 100 kW. Consumers above this limit tend to use half-hourly metering. The non-domestic model will be based on similar annual trends for end-use half-hourly demand but each half-hour will be scaled to suit the business activity – to reflect the different daily profile of demand that will arise. The ICUE tool will provide an estimated yield from solar-thermal or PV panels associated with a given node. The estimated output will then be used either to modify the modelled water heating demand or to reduce the total demand.
CASE STUDY

The SEnTINEL tool is designed for urban areas and for validation purposes, a case study will be conducted, covering an inner city area of Leicester in central England. Two feeders from a primary transformer have been selected, with over two thousand nodes, including a mix of domestic and light non-domestic consumers and of built forms, to test the irradiation aspects of the tool. Nodes have been identified from maps provided by Leicester City Council and network data from East Midlands Electricity (EME). The total demand estimated by the load model for each feeder will be compared with half-hourly measured data provided by EME, for at least one annual cycle. The match between the scale and pattern of demand will be used for calibration.

Photogrammetric data for the area has recently been acquired and is being used to build a 3D model using CAD. The ICUE model will provide annual irradiation maps and within the SEnTIENT interface, appropriate sites will be selected for assignment of PV and solar-thermal panels. The load models and irradiation predictions will provide a time-varying pattern of distributed demand over the network area. The results will be fed into the network analysis tool to perform the unbalanced three-phase power flow investigation. The GIS interface may be used to visualise the effects and areas of concern within the network supply. Reports can then be generated which examine the statistics of performance.

The prime motivation for the Solar City project is to examine in detail, the effects of different levels of uptake of solar technologies. The results are intended to provide guidelines to DNOs and urban planners. Such issues as the effect of the density of solar technologies, targeting certain types of consumer for peak reduction or design rules for connection to the LV network are likely to feature in the planned dissemination. However, the tool should provide a useful basis for wide-ranging investigations of electrical energy demand issues.

CONCLUSION

A detailed understanding of the distributed load is required to assess the potential effect of solar-technologies on LV networks. Few load models provide sufficient information to describe the high degree of diversity between consumers and the time-varying nature of the individual demand. Whilst a number of different approaches already exist the requirements of the study have led to the development of a unique, fine-grained load model.

The SEnTIENT load model aims to provide a realistic picture of demand, representing the diversity arising from ownership, efficiencies and use patterns. The relatively simple basis for the annual predictions of demand provides estimates that match well with measured data. Used within the SEnTIENT package, together with components to represent the application of solar-technologies and to analyse power flows, they should provide a better understanding of the LV network performance. This in turn will enhance the knowledge of DNOs and local planners and improve confidence in dealing with renewable energy options.

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