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Thomson, Murray, David Infield, Melody Stokes, Mark Rylatt, John Mardaljevic, and Kevin J. Lomas. 2019.
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SECONDARY DISTRIBUTION NETWORK POWER-FLOW ANALYSIS

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ABSTRACT

Existing design methods for sizing conductors in secondary distribution networks (LV networks – typically below 500V) often employ Diversity Factors and rely heavily on a wealth of experience with similar networks and similar loads. The introduction of photovoltaic (PV) systems and micro co-generation (domestic combined heat and power: DCHP) will inevitably alter power flows in these networks, but since, at present, these distributed generators are few and far between, there is little data or experience on which to predict any effects they may have when widely installed. This paper describes on-going development of thorough and detailed modelling techniques, applicable to secondary distribution networks, using 1-minute time-series data and accurate unbalanced power-flow analysis (load-flow). These modelling techniques will provide a sound basis for the consideration of micro distributed generators.

KEY WORDS

Distributed Generation, Micro-Generators, Photovoltaics, Network Analysis

1. INTRODUCTION

Distributed generators alter the power flows in distribution networks. This can lead to localised over-voltages or exceedance of thermal limits, and these factors can present an upper limit to the allowable installation of generators in an existing network. Indeed, the risk of over-voltage is often the limiting factor for the connection of wind-turbine generators to primary distribution networks (typically 10–20kV), and the cost of reinforcing the network can be substantial.

Installation of photovoltaic (PV) systems and micro co-generation (domestic combined heat and power: DCHP) could face similar limits regarding connection to existing secondary distribution networks (LV networks – typically below 500V). Furthermore, increased use of solar water heating and improved architecture could dramatically reduce electricity consumption for heating and cooling,

which would also alter network power flows. The authors are currently developing simulation software to investigate and quantify the potential effects of solar energy technologies and DCHP on existing distribution networks. The project is divided into two areas: load/generation modelling and network analysis.

Load models are very well established for the purposes of predicating bulk generation requirements and bulk power flows. However, these models are designed to predict the aggregated loads of large numbers of customers, and do not, therefore, represent the highly stochastic nature of individual customer loads. Such models are of limited value in modelling power-flows in secondary-distribution networks. Other models exist that do predict energy consumption for individual properties, but these tend to provide only monthly or annual average data, which again is of limited value in modelling secondary-distribution networks. To address this, the authors are currently developing load and generation models that will provide data for individual properties at one-minute intervals [1]. This will fully represent the highly stochastic nature of individual customer loads and will be used as input to the network power-flow analysis software being developed in parallel, and discussed in remainder of this paper.

Computer modelling of power flows in high-voltage transmission networks is long-established, typically using Newton-Raphson or Gauss-Seidel iterative methods or embellished versions of these. Balanced 3-phase operation is often assumed, though many commercial software packages can now perform unbalanced analysis, if the necessary additional data is available. Such software has also been extensively used to model primary-distribution networks, though the Newton-Raphson algorithm can sometimes fail to converge, due to high R upon X ratios. Alternative algorithms, exploiting the radial nature of distribution networks, have been developed by Kersting [2] and Shirmohammadi [3] over the last decade. This approach, known by Kersting as the Ladder Iterative Technique, involves making forward and backward sweeps through the network, and avoids the need to construct and manipulate a large network-admittance matrix. It has good convergence

characteristics, can include detailed non-linear models of tap-changing transformers etc. and is highly efficient for networks with large numbers of nodes.

Any of the power-flow analysis algorithms mentioned above can be applied to secondary-distribution networks; however, the highly stochastic nature of individual loads renders any single-point-in-time “snapshot” analysis of very limited value. Traditionally, the stochastic nature of individual loads is accommodated by use of Diversity Factors [4]. Ideally, diversity factors should be determined through a comprehensive survey of local loads. In practice however, it is usual to rely on decades of experience with similar loads, which is valid, provided that the loads can be expected to have similar behaviour in the future. This however may not be the case, if there is significant uptake of solar-energy technologies or DCHP or both.

2. POWER-FLOW ALGORITHM

Monte-Carlo versus Probabilistic

In a Monte-Carlo simulation, a single-point-in-time power-flow algorithm is run repeatedly with loads sampled from appropriate probability distributions. If a large number of time-series values are available, the approach can be reduced to simply undertaking a steady state load flow for the data corresponding to each time step. A more elegant, probabilistic, approach manipulates the probability density functions directly as part of the power-flow solution algorithm. Earlier research at CREST [5] [6], implemented two alternative probabilistic power-flow algorithms. This work demonstrated the difficulties of probabilistic power-flow, particularly regarding the handling of partial correlations. Also, because the fast Fourier transforms employed to manipulate the probability density functions are computationally intensive, the work failed to demonstrate any significant reduction in overall computing time, when compared with the Monte-Carlo approach. Consequently the latter approach has been adopted for the project in hand.

Newton-Raphson versus Ladder-Iterative Technique

With Monte-Carlo simulation, the single-point-in-time power-flow algorithm is run a great many times and must therefore be very fast in itself. The authors wrote single-phase (balanced) versions of both Newton-Raphson and Ladder-Iterative algorithms in MATLAB. Both were carefully written, with regard to execution time, and made full use of MATLAB’s powerful matrix-manipulation functions. The two programs were tested on a typical radial rural 11-kV primary-distribution network with 328 nodes. They both converged within 5 iterations. The Newton-Raphson algorithm took just over 5 seconds, whereas, the Ladder-Iterative algorithm took under 0.5 seconds. This tends to confirm the findings of other researchers [3], although it should be noted that

comparisons of this kind are very sensitive to the chosen test network and unintentional differences in programming efficiency. The Ladder-Iterative algorithm was selected for use in this project.

Unbalanced Power-flow

At the primary-distribution level, it is sometimes reasonable to assume balanced operation and to conduct power-flow analysis on that basis. (Often, the assumption is not entirely sound, but is made anyway because individual phase data is not available.) At the secondary-distribution level, balanced operation cannot normally be assumed and unbalanced analysis is a necessity.

The extension of the balanced Ladder-Iterative program, described above, to perform unbalanced 3-phase power-flow was fairly straightforward: – because well-structured MATLAB code uses matrixes in preference to “for” loops, the extra dimension is readily accommodated. The program was checked against a leading commercial distribution-network analysis package and the results were virtually identical.

The greatest challenge lay in obtaining the cable impedance parameters relevant to unbalanced operation. Some cable manufactures list sequence impedances for high-voltage cables but no such values are readily available for 600/1000-Volt cables. Clearly, unbalanced analysis of low-voltage networks is rarely attempted.

3. TEST NETWORK

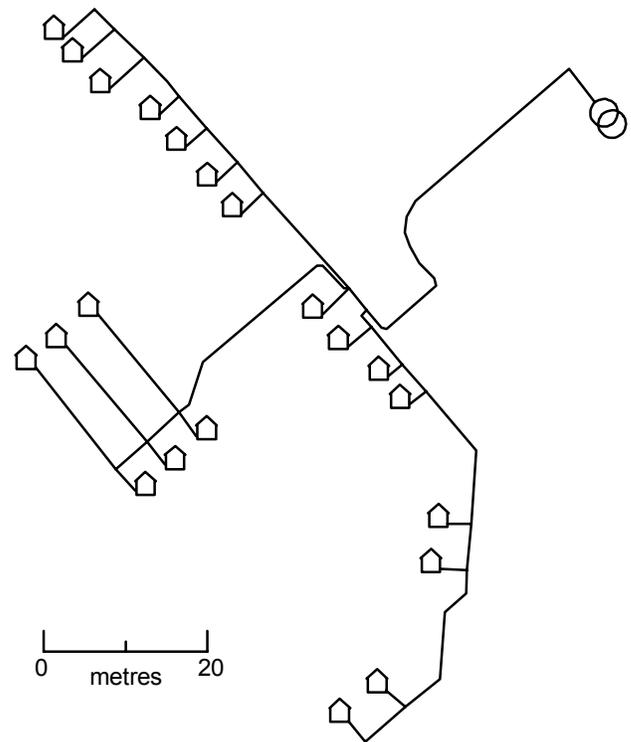


Figure 1 – Test Network

Testing of the software was carried out on a 400/230-Volt secondary-distribution circuit in city-centre Leicester, Midlands, UK. The circuit has 40 nodes and feeds 21 houses, as shown in Figure 1. The locations and cable types of the 3-phase mains were accurately modelled, according to the network operators' database. The locations and cable types of the single-phase services to individual houses were assumed and the choice of phase randomly generated.

The source voltage, at the secondary of the distribution transformer, was taken as 400 V exactly. Clearly this will vary in practice, and it would be very much better to model the whole primary-distribution feeder and all its secondary-distribution circuits, which is the intention in due course.

4. LOAD DATA

The detailed load models, mentioned in the introduction, are not yet complete and so measured load data from 15 houses elsewhere in the Midlands, UK, was employed for

demonstration purposes. (Data from all 15 houses recorded on Wed 14-Dec-0095 was used, together with data from 6 of the same houses recorded on Wed 15-Dec-0094.) The data was recoded at 1-minute intervals and displays the highly stochastic nature expected of individual house loads.

It is common to describe loads as constant-power, constant-current, constant impedance or any combination of these, and this can readily be accommodated in the power-flow analysis program. For measured power data, as in this case, the constant-power model is appropriate and was employed.

Reactive power had not been measured so a power factor of between 0.94 and 0.98 was randomly assigned for every data point. This caused the reactive power data to be even more stochastic than the active power. For comparison, a constant power factor of 0.96 was used, and made virtually no difference to the overall results. The load models, mentioned in the introduction, will include estimation of reactive power based on end-use.

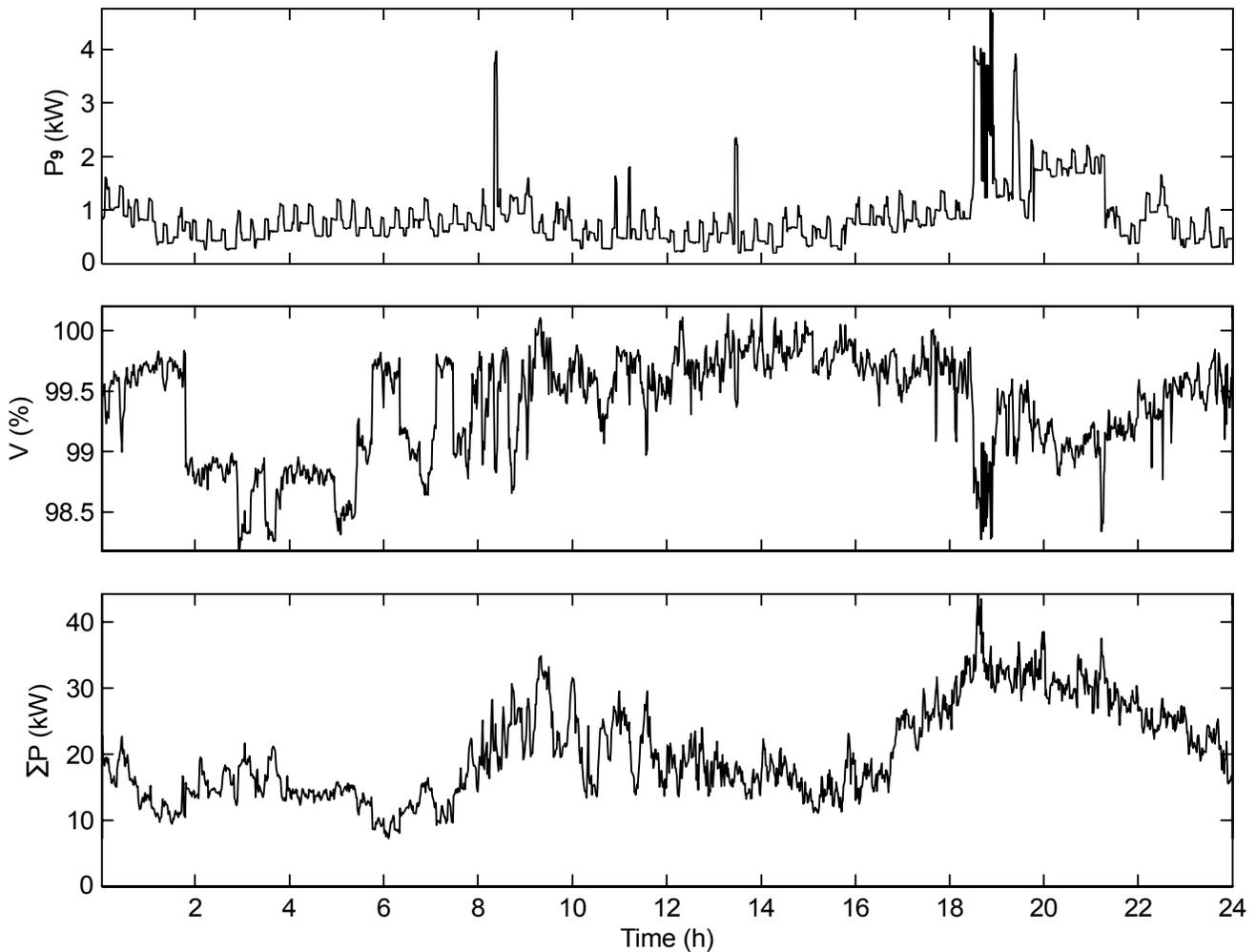


Figure 2 – Example power-flow analysis results

5. RESULTS

One full day's operation of the test network was simulated at 1-minute intervals. This is 1440 time steps and, at each time step, the software calculates 3-phase complex voltages and currents throughout the 40-node network. The whole analysis takes around 100 seconds to perform, which is very respectable at this early stage of development. The program is currently written in MATLAB that is interpreted at runtime. There are various routes through which performance could be dramatically improved.

Some example results are shown in Figure 2. The top graph shows the active power consumed by one of the houses with respect to time throughout the 24-hour day (input data). The highly stochastic nature of an individual customer load is immediately apparent. The middle graph shows the percentage voltage at the same house calculated by the power-flow software. (Recall that this demonstration assumes 100% voltage at the source node. When the rest of the network is considered voltage variations will be much greater.) The bottom graph shows the aggregated load of all 21 houses. The "smoothing" of the load profile through aggregation is apparent.

Retuning to the middle graph (calculated voltage), it can be seen, as expected, that the voltage is depressed around 19:00h when the house load is high. However, the voltage is also depressed during the night; this is due to a neighbour's off-peak heating system and could not have been anticipated from house's own load profile or from the aggregated load profile. Close inspection of the middle graph reveals that the voltage occasionally exceeds 100%. This is due to neutral voltage displacement, and is to be expected in unbalanced 3-phase systems. These points demonstrate that voltage prediction in such networks is not entirely intuitive.

Similar graphs for all the other houses can readily be plotted and examined; likewise conductor currents, losses etc. can be studied. The network area can be increased to include many more houses and the time frame may be extended. Clearly, manual interpretation of the results will quickly become impossible. To address this, post-processing will be provided to identify, for example: frequency of voltage excursions.

6. CONCLUSIONS

Improved power-flow analysis techniques are required for secondary distribution networks, in particular to predict effects caused by significant uptake of solar-energy technologies or DCHP or both. The authors are currently developing such techniques and this paper has discussed the selection of the power-flow analysis algorithm: Monte-Carlo application of an Unbalanced Ladder-Iterative Technique. Initial results are promising and the work is ongoing.

7. ACKNOWLEDGEMENT

This research is funded by the Engineering and Physical Sciences Research Council, UK, project number GR/N35694/01.

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