SWITCHING TRANSIENT ANALYSIS OF SMALL DISTRIBUTED GENERATORS IN LOW VOLTAGE NETWORKS

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ABSTRACT

This paper details work undertaken to determine the severity of switching transients arising as a result of the G83/1 grid disconnect requirements of type-tested microgeneration equipment. Models of a generic domestic electricity supply and simple urban and rural low voltage networks are constructed in ATP-EMTP, and a series of generator switching operations simulated.

It was found that, on the customer supply side, the combination of high generator output and low instantaneous domestic load led to overvoltage magnitudes of 1.4 p.u. At distribution level, a direct correlation was found to exist between the number of generators on a feeder and peak overvoltage magnitudes on that feeder. Worst case scenarios were identified for further detailed study, and a number of model refinements would be required.

INTRODUCTION

With mounting concern over energy security, growing public opposition to conventional power generation on environmental grounds and the increasingly uncertain economics and politics of fossil fuel supply, there are set to be major changes in the way in which our electrical energy is generated, distributed and utilised. Small scale embedded generation technologies are likely to make a useful contribution to government targets through customer side demand reduction and community energy projects, potentially contributing more than 15GW to the UK’s energy mix by 2020 [1].

To date, a large number of studies have been published on energy yield maximisation and ancillary service provision capability of such sources, either through the use of sophisticated interface and storage devices, or using various aggregation techniques. Little attention however has yet been given to fast transient overvoltages occurring as a direct result of generator switching operations. On the customer side of the meter, such overvoltages may damage equipment and appliances, while in small industrial premises other problems such as nuisance tripping of variable speed drives may occur [2].

With the ambitious energy efficiency and generation sustainability targets for 2020 fast approaching, the UK’s networks need to adapt in order to integrate the vast amounts of distributed energy sources required. At the demand side, small scale generators rated below 16A per phase will likely make a significant contribution to meeting these targets, and as such a great deal of research has focused on maximising the time-value and energy yield of such sources. Little attention, however, has yet been paid to fast transient phenomena relating to their use.

In the UK and across Europe, microgeneration in the form of small wind turbines, photovoltaic panels or micro CHP units may be type-tested to reduce the complexity and duration of the commissioning process. One of the conditions of this type-testing is that grid-connected generators must disconnect from the supply when significant voltage or frequency deviations occur, reconnecting again following a pre-defined delay. The conditions for these switching operations are given in the UK Energy Networks Association Engineering Recommendation G83/1 [3], and also in its equivalent draft British Standard BS EN 50438 [4].

This paper presents work undertaken to model domestic electricity supplies with single phase generators rated up to 3.7kW (16A) in ATP-EMTP. Simple models of urban and rural LV networks are also constructed in order to investigate the impact of switching transients at distribution level. A range of relay connection and disconnection operations are simulated in accordance with G83/1, in order to estimate the impact of source rating, local loading and network architecture on switching overvoltage magnitudes.

MODELLING AND SIMULATION

In this section, the construction of domestic supply and LV network models is briefly discussed. Assumptions and simplifications made during the initial modelling process are indicated, together with practical considerations relating to the precision and execution time of the final simulations.

Generic Domestic Model

In order to investigate the impact of generator switching operations at the source, behind the customer’s meter, a generic consumer supply and load model was constructed. A set of typical consumer loads, such as incandescent and fluorescent lighting, space and water heating, ovens, hobs, refrigerators and various consumer appliances were approximated based on typical ratings and power factors, using lumped RL elements. These loads were fed from the consumer unit bus by lengths of PVC insulated two-core and earth cabling, in either radial or ring configurations.

The customer bus was in turn fed from a reference grid supply behind its equivalent surge impedance and a length...
of 120mm² underground cable, together with a local source representing the installed microgeneration device. The earthing arrangement was TN-C-S for this particular study. Figure 1 shows a line diagram of the constructed model.

Fig 1. Line diagram of the generic domestic supply and load model

Modelling of the long underground feed was achieved using geometric cable pipe transmission line sections. This approach was not used for the domestic wiring out of consideration for the simulation execution time. It was determined that for a propagation velocity in PVC of approximately $1.6 \times 10^8 \text{ms}^{-1}$, short cable lengths of a few metres each would require a simulation time step of roughly 1ns in order to return dependable results. It is, therefore, justified to represent these cable lengths using lumped RLC equivalents. Inductance and capacitance values were calculated from [5, 6], while high frequency resistance values were calculated with reference to skin and proximity effects from [7].

Low Voltage Distribution Models

Urban Cable Network:
Figure 2 gives an illustration of the simple urban LV distribution network model constructed in order to study the cumulative impact of multiple generators on a feeder.

Fig 2. Simple urban LV cable network with microgeneration

With minimum lengths of 50m of XLPE insulated cable sections, the shortest propagation times were limited to approximately 250ns. It was deemed that a 10ns time step would be acceptable with regard to execution time and output file size, allowing all cable sections to be modelled as transmission lines. A simplification of the model was achieved by using a single conductor cross-section of 120mm² [8] to maintain constant surge impedance between the LV transformer and the customer loads. This would keep the number of reflections observed to a minimum, improving the clarity of results, though a more accurate model could easily be implemented.

Three discrete domestic load profiles were adopted using lumped RL elements: (i) A 200W minimum load, representing typical, household base loads such as refrigeration and equipment standby modes; (ii) a 1kW normal load, representing general occupancy demands such as lighting, computers and entertainment equipment; and (iii) a 5kW heavy load to represent peak demands of cooking, space and water heating, washing, drying and various high power appliances. A typical constant power factor of 0.97 lagging is assumed in each case to allow direct comparison of results.

For the purposes of these first studies, disconnection and reconnection of the generators is achieved using timed switches. Coincident switching operations are assumed to give a worst-case scenario, though in a real system such operations would be randomly dispersed within a finite time window. Such behaviour could be simulated through the use of systematic or statistical switching and will likely form the basis of further study.

Rural Overhead Line Network:
A similar generic study network was constructed to simulate the effect of transients in rural overhead line distribution networks. An indicative line diagram of the model is given in Figure 3. The minimum length of transmission line section in this case was 300m, so simulation time step was not a critical constraint. 9-metre wood poles with a phase to phase separation of 30cm were used, and the conductor geometry was selected from [9] to give a constant cross section area of 106mm².

Fig. 3. Simple rural overhead line network with microgeneration
RESULTS

Customer Side

The generic domestic supply model was used to simulate the impact of customer load and generator rating on overvoltage magnitudes within the home. Individual generator switching operations were performed over a half-cycle time window using a systematic switch in order to obtain worst case voltage maxima. Table 1 gives the peak voltages observed at the consumer unit for each combination of generator output and consumer load, where the generator is switched into the customer bus.

<table>
<thead>
<tr>
<th>Rating</th>
<th>No Load</th>
<th>Minimum Load</th>
<th>Normal Load</th>
<th>Heavy Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1kW</td>
<td>1.01</td>
<td>1.01</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2kW</td>
<td>1.01</td>
<td>1.01</td>
<td>1.02</td>
<td>1.00</td>
</tr>
<tr>
<td>3kW</td>
<td>1.21</td>
<td>1.22</td>
<td>1.21</td>
<td>1.05</td>
</tr>
<tr>
<td>3.7kW</td>
<td>1.40</td>
<td>1.40</td>
<td>1.39</td>
<td>1.10</td>
</tr>
</tbody>
</table>

It can be seen that appreciable overvoltages of around 140% only occur where the output of the generator significantly exceeds the local loading at the instant of switching. Such a situation could occur in a large home under night time load (in the case of a wind turbine) or where the house is unoccupied for any significant length of time. Should the economics of microgeneration become favourable, systems which are overrated relative to customer load as a means of generating income would also fall into this category. In the majority of cases, however, the impact of a single generator would likely be negligible. No significant overvoltages were observed as a result of disconnection operations.

Network Side

For the urban and rural network models taking account of multiple distributed generators, the rating of the sources had far less of an impact on switching overvoltage magnitudes than on the customer side. Peak voltages were found to depend far more on the instantaneous loading of the feeders, and on the number of generators being connected or disconnected. The results presented are taken from probes distributed at regular intervals along a single phase of the network, and are the maximum values observed at any one of those measurement points. The results of switching in different numbers of 1kW microgenerators under various loading scenarios in an urban network are given in Table II.

<table>
<thead>
<tr>
<th>Number of Generators</th>
<th>Minimum Load</th>
<th>Normal Load</th>
<th>Heavy Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.09</td>
<td>1.00</td>
<td>1.03</td>
</tr>
<tr>
<td>3</td>
<td>1.04</td>
<td>1.019</td>
<td>1.073</td>
</tr>
<tr>
<td>10</td>
<td>1.012</td>
<td>1.054</td>
<td>1.163</td>
</tr>
<tr>
<td>30</td>
<td>1.078</td>
<td>1.262</td>
<td>1.473</td>
</tr>
</tbody>
</table>

The results show an increase in peak voltage with both the feeder load and the number of coincident switching operations. These relationships are illustrated in Figure 4.

![Fig. 4. Variation of peak overvoltages in an urban network with number of generators and local instantaneous load (switching in).](image)

Fig. 4. Variation of peak overvoltages in an urban network with number of generators and local instantaneous load (switching in).

Similar behaviour occurred for generator disconnection, though significant overvoltages were only observed when a large number of generators were involved, as shown in Figure 5.

![Fig. 5. Variation of peak overvoltages in an urban network with number of generators and local instantaneous load (switching out).](image)

Fig. 5. Variation of peak overvoltages in an urban network with number of generators and local instantaneous load (switching out).

Results for the rural network model show a very similar relationship, though similar overvoltage magnitudes were achieved using far fewer generators, implying that rural networks would be far more susceptible to switching overvoltages where multiple sources are involved. The computed peak values are summarised in Table III.

<table>
<thead>
<tr>
<th>Number of Generators</th>
<th>Minimum Load</th>
<th>Normal Load</th>
<th>Heavy Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.023</td>
<td>1.056</td>
<td>1.175</td>
</tr>
<tr>
<td>3</td>
<td>1.213</td>
<td>1.234</td>
<td>1.364</td>
</tr>
<tr>
<td>5</td>
<td>1.456</td>
<td>1.477</td>
<td>1.564</td>
</tr>
</tbody>
</table>

These results show a more linear relationship between numbers of generators and peak voltages than is seen in the urban model. This would suggest that predicting and mitigating hazardous switching overvoltages in rural networks would be easier than in urban cable systems. This linearity can be seen in Figure 6. As observed before, disconnecting generators caused no significant overvoltage.
For all of the network scenarios considered, peak voltage at the terminal of the LV transformer remained below 1.15 p.u. Therefore, extra overvoltage protection of the transformer secondary is not likely to be required as a result of this. Larger overvoltages in the region of 1.4 to 1.6 p.u. were computed towards the remote end of the radial feeder in cases where microgenerator penetration was high. Transient voltage suppression may be required in such cases to protect customers on this section of the feeder.

Analysis of an individual customer supply has shown that in the vast majority of cases, individual switching operations are no cause for concern. Overvoltage limiting devices for all type-tested generators would, therefore, be unnecessary and uneconomical, with case-specific protection schemes being the preferred option. The performance of such devices will be the subject of further study.

Having identified a number of worst case scenarios, more detailed analysis can now be performed to take account of different conductor geometries and realistic non-simultaneous switching of generators. An LV feeder construction similar to that presented in [10] would be an excellent basis for further large scale analysis. Improved modelling of the source interface will also produce results which better represent the fast transient behaviour of a real system.

**CONCLUSIONS**

Switching transient analyses of a single small distributed generator in a typical household and multiple generators feeding generic urban and rural LV feeders have been performed in EMTP. It was found that the reconnection via an electromechanical relay of a single generator into the domestic supply, following a drift in system voltage or frequency as per BS EN 50438, caused overvoltages of up to 1.4 p.u. at the consumer bus. It was found that maximum peak voltages occur where local generation greatly exceeds the customer’s load, and are particularly pronounced where local load is at its minimum.

Multiple switching operations lead to overvoltages in the LV network which were dependent both on feeder loading and on the number of coincident switching operations. Peak voltages observed were around 1.5p.u. for high penetration in an urban cable network, and 1.6p.u. for a rural network. Those simulation configurations which produced the most pronounced overvoltages were identified for further detailed study, and suggestions for the refinement of the generic model and extension of this investigation have been made.

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**REFERENCES**