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# IMPACT OF HIGH PENETRATIONS OF MICRO-GENERATION ON LOW VOLTAGE DISTRIBUTION NETWORKS

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## ABSTRACT

*Due to rising fossil fuel and electricity prices and the overall need to reduce carbon emissions, there is a growing interest in the utilisation of micro-generation amongst electricity consumers and governments alike. Electricity consumers are installing small scale generators on their premises, which are also being connected to existing low voltage (LV) electricity supply networks. High penetrations of micro-generation may present challenges to the planning and operation of LV electricity networks. This is due to LV distribution networks being designed for delivery of electricity from sub-stations to the consumers and not for accommodating generation. The aim of the work presented in this paper is to examine the effect of high penetrations of micro-generation on the voltage levels of a section of existing Irish LV distribution network.*

## INTRODUCTION

There is growing interest in utilising small scale generating units for electricity and heat energy production at the point of consumption. Reasons for this increased interest include consumers wanting to reduce their heat and electricity costs while also becoming less affected by changing energy costs due to present and future uncertainty in fossil fuel prices. Governments across the world are also looking to reduce overall carbon emissions and meet renewable energy targets and micro-generation is seen by many as having a key part to play in future generation portfolios [1-3].

Micro-generation can be described as the small scale production of heat and/or electrical energy from low carbon sources. Micro-generation units are normally defined as generating units with rated capacities of 50 $kW_e$ or less and are usually connected to LV distribution networks, which are typically radial in nature. They exist in a number of different technology types that can include photovoltaic cells, micro-wind turbines and small scale hydro for the production of electricity and solar water heating, biomass and ground source heat pumps for heat energy. There is also technology available that is capable of providing both heat and electrical energy. These technologies are generally described as micro combined heat and power (micro-CHP) units. Currently, this type of generation is mainly based on Stirling engine technology. In the future, fuel cell technology may also be utilised on a large scale as a form of micro-CHP. A widespread uptake of any of the above technologies will depend on a number of factors such as technological and economic status, government incentives, consumer behaviour and the technical issues which may arise as a result of a large scale implementation of the units on the LV network. It is the last factor that is the basis of investigation for this work.

There is very little uptake of micro-generation technologies in Ireland at present. This is mainly due to the financial aspects involved with installing and operating micro-generation units. Until recently in Ireland, there has been no method for metering electricity that is exported back into the grid. Trials are currently taking place to investigate the effects of electricity being sold back to the network operator [4]. As micro-generation technologies develop the initial investment cost of the various units should decrease. This coupled with suitable methods for metering electricity exported back into the grid [5] and the establishment of reward schemes for carbon savings should see a much wider uptake of the technology in the future. In the case of such a large integration of micro-generation, the distribution network operator must ensure that no network constraints are exceeded. Such network constraints include thermal constraints, equipment ratings and voltage rise.

Previous work carried out in the area of micro-generation has sought to investigate the technical impact on the LV network [6-8] and the economic impact [9-12] from different forms of micro-generation. The work detailed in this paper aims to investigate the impact from widespread implementation of micro-generation on voltage levels, in particular, of existing LV networks from a number of different aspects. This is done by performing unbalanced three-phase AC load-flow analyses on sections of LV network with varying levels of micro-generation. The LV network sections are modeled using DIgSILENT Powerfactory software [13]. The majority of the tests carried out involved examining a single line. Other lines are required in the model in order to examine the network under contingency conditions. The test network, micro-generation and load modeling details are given in the following section. The results of the tests are then examined in the Results and Discussion section. Possibilities for future work in this area are outlined in the final section.

## TEST MODEL

### Test Network

The test network used in this work represents a section of LV distribution network in the suburbs of Dublin in Ireland. The actual network model as it appears in the Powerfactory software is large and quite detailed. For the purposes of this paper, a simplified version of the network is shown in Figure 1.

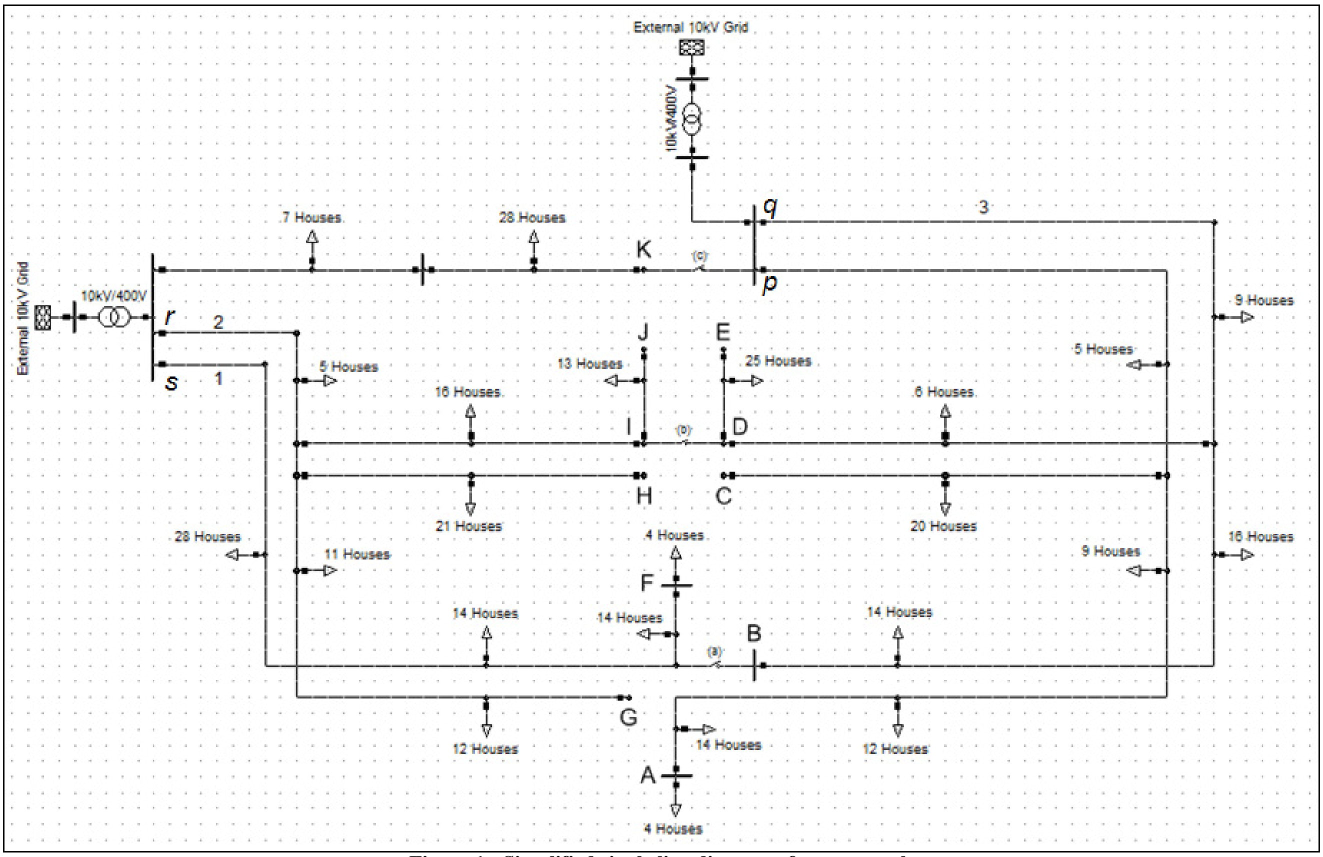


**Figure 1 - Simplified single line diagram of test network**

In Ireland the nominal voltage on the LV distribution network is 400Vp-p/230Vp-n and the voltage range tolerance is the nominal voltage +/–10%. The sending voltage at the feeder buses is +5% of the nominal voltage [14]. Data for the network model was provided by Electricity Supply Board (ESB) Networks [15]. ESB Networks are the distribution network operator in the Republic of Ireland, responsible for the operation and maintenance of all distribution networks in the Republic of Ireland.

The test network model is radial and consists of two 10kV/400V transformers supplying a total of 307 (400/230V) domestic loads on two separate sections of LV network. It is made up of 3.1km of 3-phase-neutral mains cables and 2.3km of 1-phase-neutral service cables. The mains cables varied in type with 120mm$^2$ Cu, 70mm$^2$ Cu and 50mm$^2$ Cu cables used at different parts of the network. Under contingency conditions, it is possible for the two sections of network to connect via normally open connection points located at various points in the network.

## Micro-generation Modeling

The electrical output of some types of micro-generation cannot be actively controlled, e.g. PV cells, micro-wind turbines. Other forms of micro-generation, however, can be actively controlled and their electrical/heat energy can be utilised on demand, e.g. micro-CHP units. Micro-generation units were modeled on the test network as PQ injections at each house. Individual micro-generation units were rated with electrical outputs of 1-1.2 kW$_e$. This is similar to the rated capacities of Stirling engine micro-CHP units that are currently available on the market [16]. These units were operated at a power factor of 0.98 inductive.

Domestic micro-CHP units can be switched on by the owner/operator as required. However, they usually operate at times of day when heat, usually for hot water, is required in a building. This normally occurs during the morning period, between 6 a.m. and 10 a.m. and to lesser extent again in the evening, between 6 p.m. and 10 p.m. [6]. Electrical energy is only produced as a byproduct of the heat energy and as such will only be produced when heat is demanded in the building.

## Load Modeling

Load data for domestic electricity demand was obtained from the distribution network operator. It consisted of time-series data representing the electricity demand for typical high, medium and low use customers for a one year period. The worst case scenario for voltage rise occurs when a network is operating under conditions of minimum load demand. As the tests carried out in this work consisted only of snap-shot analyses of the test network a minimum load of 0.1kW was assigned to each domestic building. This figure is the average load demand by a low use customer between the times of 6 a.m. and 10 a.m. over the period of one year. This time of day is chosen for analysis as it coincides with the time of day when most micro-CHP units would be operating.

## RESULTS AND DISCUSSION

### 100% Penetration of Micro-generation

Initially, the network was analysed with a 100% penetration of micro-generation, i.e. a 1.2kW generator operating at each building. The voltages at the terminals marked in Figure 1 are given in Table I. Voltage levels are also given for the same terminals when the network is operating under contingency (*n*-1) conditions. The "Line End" terminal is the terminal at the end of the line which is out of service in each case. (a) and (b) indicate the normally open connection points that are closed in each contingency case. The shaded voltages in the results table indicate those which exceed the distribution network voltage tolerance of 230V+10% (i.e. 253V).

These results demonstrate how the voltage levels on the network are affected under various contingency conditions. When the network is operating under conditions of minimum electricity load and maximum electricity generation, with 100% penetration of micro-generation, the voltage levels are mostly within the safe operating limits albeit close to the upper limit of 253V. This shows that, for different levels of demand and generation, the voltage levels of the network would be within the constraint limits. This is dependent on electricity demand, length of line, number of houses and quality of mains cable supplying the electricity. This can be seen when the network is operating under *n*-1 line conditions. When a line has to be switched out, a normally open point will be closed in order to supply the area that has lost its supply. In this situation the length of the line from the transformer and the number of houses on that line will increase. From the tests carried out above, the voltage levels at certain points on the network can reach as much as 16% above the nominal voltage of 230V.

| | Network Cable Out of Service | | | | | |
|---|---|---|---|---|---|---|
| Terminal | - | 1 | 2 | 3(a) | 3(b) | 3(a&b) |
| A | 254.9 | 257.3 | 258.1 | 252.1 | 252.1 | 252.1 |
| B | 253.3 | 263.1 | 259.4 | 259.3 | 259.2 | 253.1 |
| C | 252.5 | 254.9 | 255.6 | 249.7 | 249.7 | 249.7 |
| D | 252.7 | 257.4 | 260.7 | 264.7 | 257 | 253.6 |
| E | 253.9 | 258.6 | 261.9 | 265.9 | 258.1 | 254.8 |
| F | 249.7 | 263.6 | 250 | 259.5 | 249.5 | 253.3 |
| G | 248.1 | 248.3 | 266.5 | 247.9 | 251 | 249.8 |
| H | 248 | 248.2 | 266.4 | 247.8 | 250.9 | 249.7 |
| I | 248.5 | 248.7 | 261.1 | 248.3 | 256.6 | 253.4 |
| J | 249.1 | 249.3 | 261.7 | 248.8 | 257.1 | 253.9 |
| K | 247 | 247.2 | 247.3 | 246.8 | 246.8 | 246.8 |
| Line End | - | 266 | 265.4 | 264.1 | 258.1 | 254.1 |

**Table I - Terminal voltages (V) for network with 100% penetration of micro-generation under *n* and *n*-1 condition**

### Quantity and Location of Micro-generation

Under the same conditions of minimum load and maximum generation as in the previous test, micro-generation units were added to the system incrementally in order to find the maximum number of units that would be possible to operate on the network while remaining within voltage constraint limits. Two separate situations were examined. In Case A, units were kept as close to the transformer bus as possible. In Case B units were kept as far from the transformer bus as possible. In both cases, the lines beginning at points r and s could accommodate 100% penetration while remaining within acceptable voltage limits. The results for the lines beginning at points p and q are given in Table II.

| | Line p | Line q |
|---|---|---|
| Case A | 83%-86% | 88%-94% |
| Case B | 62%-73% | 77%-97% |

**Table II - Maximum percentage penetrations of micro-generation units on lines beginning at points p and q**

A range of percentages for the lines arise in each case due to the interaction of the lines as a result of being connected at the same bus. It is also due to the different arrangements possible for a given number of houses on both of these lines.

The model was then tested under contingency conditions in order to establish a maximum penetration level while operating with *n*-1 lines. The network model is examined with Cable 2 out of service as this situation results in the most severe voltage rises across the network (see Table I). In this situation the normally open point (b) will close and connect lines q and r. Results are shown in Table III.

| | Line p | Line q+r |
|---|---|---|
| Case A | 84% | 45% |
| Case B | 100% | 23% |

**Table III - Maximum percentage penetrations of micro-generation units on lines p and q+r with Cable 2 out of service**

Under *n*-1 line conditions, the percentage of the total number of houses on a line that are capable of operating a micro-generation unit, while keeping the network within the voltage constraints, was shown to be as low as 23%. This is a relatively low number of houses and could become a serious issue if an unexpected fault occurred in the network.

### Effect of Location of Micro-generation

Due to the radial nature of distribution networks, the terminal along any line that is likely to be most affected by any level of micro-generation penetration is the end terminal of that particular line. The end terminal voltage for a particular line on the network (Figure 2) was recorded for varying levels of micro-generation penetration on the line. The line was 527m in length with 44 houses connected. Details of the line tested are given in Table IV.

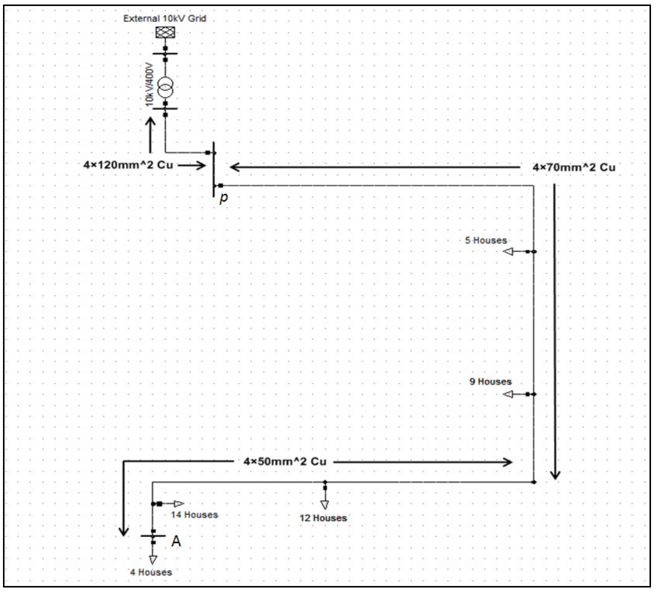


**Figure 2 - Line tested for effect of location of micro-generation**

| Cable Type | Length | Number of Houses |
|---|---|---|
| 120 mm$^2$ Cu | 190 m | 0 |
| 70 mm$^2$ Cu | 183 m | 14 |
| 50 mm$^2$ Cu | 154 m | 30 |
| Total | 527 m | 44 |

**Table IV - Line Data**

Results are shown in Figures 3 and 4. Once again, two cases are considered here. In Case A units were kept as close to the transformer bus as possible. In Case B units were kept as far from the transformer bus as possible. The two cases were tested in two different scenarios. In Figure 3 there is a 100% penetration of micro-generation on all other houses on the network. In Figure 4 there are no other micro-generation units on the other lines of the network. Both figures demonstrate the voltage rise at the terminal at the end of the line due to the addition of micro-generation. The difference between the overall voltage levels, shown in the figures, demonstrates the interdependence between the lines of the network. The implementation of micro-generation along one line has the effect of raising the voltage levels on the other line.

The location of micro-generation along a line is shown to have a significant effect on the voltage levels of the network. Micro-generation located far from the transformer or located on a line with higher resistance will have a greater voltage rise effect when the unit is exporting electricity back into the network. As micro-generation cannot be actively controlled by network operators, any units which potentially could cause voltage rise problems would not be allowed to connect to the grid for electricity export. Smart metering technology capable of allowing the network operator some level of control over the output from micro-generation units may help alleviate this problem.

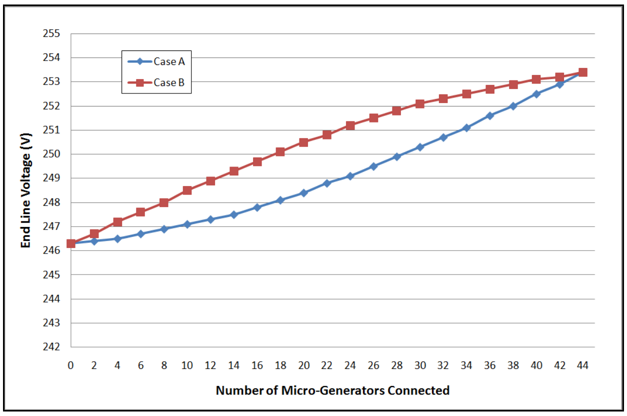


**Figure 3 - Voltage rise at end line terminal due to addition of micro-generators (100% micro-generation penetration on other lines in network)**

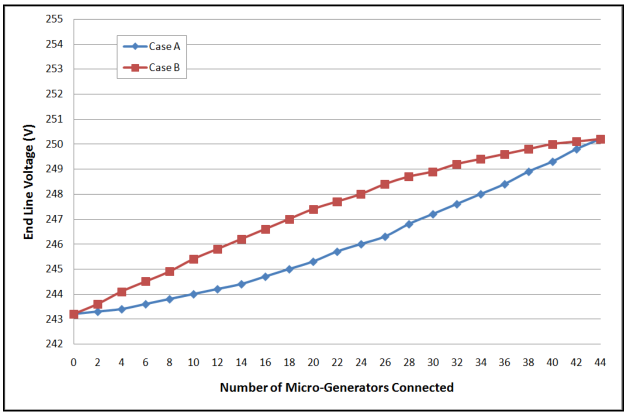


**Figure 4 - Voltage rise at end line terminal due to addition of micro-generators (no micro-generation on other lines in network)**

## FUTURE WORK

This work has shown how micro-generation units sized for domestic buildings could affect the voltage levels of a LV network. A unit is usually sized according to the energy requirements of the building. Larger buildings (e.g. schools, offices etc.) may require larger units in order to provide adequate amounts of heat or electricity. For example, micro-wind turbines can have output capacities up to 50kW$_e$ and micro-CHP units can produce up to 10kW$_e$. A low electricity demand by a building operating a unit of this size could result in a large electricity export into the network at the point of connection. This would have a greater impact on the voltage levels of the network than a smaller domestic unit would have. The full effect of larger units on the network, in terms of penetration levels and location issues, will be considered in future work in this area.

The results from this paper have shown that it is possible, in some situations, for high penetrations of micro-generation to cause a LV network to exceed safe operating limits. A time-series analysis of this network, using load and generation data for a certain period of time (e.g. one year) would show if and when situations similar to those shown in this work might occur.

The load data used in this work is averaged over 15 minute periods. Data with a higher time-series resolution may show higher or lower levels of electricity demand that may not be seen in load data of 15 minute periods. The utilisation of an optimal power flow technique should give a more accurate indication of acceptable levels of micro-generation penetration and also a better assessment of the network impact in both normal and contingency operating conditions.

## CONCLUSION

Some of the effects of a widespread implementation of micro-generation on the voltage levels of existing distribution networks have been presented. It would appear that the voltage levels can breach the network constraints only under extreme conditions of minimum load and maximum generation. However, exceeding voltage limits is shown to become a much greater concern when the network is operating in contingency situations. The location of micro-generation along existing lines has been shown to be an important issue when determining the maximum penetration of generating units on a line. Analysing the network with high penetrations of micro-generation over certain time periods would provide a better indication of how the voltage levels at particular points of the network are affected.

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