



www.ser.d.a.t.ac.th/eric

Meeting the Challenges of High Levels of Micro-Generating Technologies Connected to the Distribution Network

Forrest, D. Simon and A. Robin Wallace

Institute of Energy Systems, School of Engineering and Electronics,
The University of Edinburgh, The King's Buildings, Edinburgh EH9 3JL
SCOTLAND

ABSTRACT

Liberalised electricity industries around the world are experiencing increasing growth in renewable energy generating plant that tends to be smaller, distributed, unconstrained and connected to the lower voltage distribution network. Recent technical advances in development and falling costs of micro-generating units such as fuel cells, photovoltaics and domestic combined heat and power, that can be located in domestic homes or in small business premises, have meant that a considerable amount of the conventional electricity supply could be met by these new technologies. Domestic generation offers the potential to cut CO₂ emissions, reduce transmission and distribution losses, flatten demand peaks, improve reliability of supply and to provide a cheaper energy solution for the consumer. However, with these benefits come many operational, technical and commercial challenges for the Distribution Network Operator (DNO).

Domestic generation units will be connected to the DN in an unplanned, relatively unrestricted, unconstrained manner and will be located at the very edges of the DN. Where a large number of these units are installed in a specific area, this could lead to adverse effects on the DN. If the high levels of domestic generation that are being predicted are to be met, it will become necessary for DNOs to understand the impact on their systems all the way to the extreme edges.

In collaboration with a DNO, novel techniques are being developed to analyse the impact of domestic generation. This will determine the effects that a high level of domestic generation will have on the network. This paper explains these techniques. It then analyses the expected level of domestic generation penetration that a local DN can accommodate before it becomes detrimental to the DN's performance. Finally it discusses methods by which domestic generation can best be accommodated.

1. INTRODUCTION

Technology advances as well as political and environmental drivers have encouraged a trend within the Electricity Industry (EI) away from conventional large centralised power plants towards a system containing more distributed forms of generation. The conventional centralised electricity system typically has large, central power stations connected to the Transmission System (TS). The TS is actively managed using bi-directional power flow to bulk-transfer electricity around the country from the power stations, to the main load centres where and when it is needed. From here the electricity is transferred to the local, lower voltage Distribution Network (DN) via a Bulk Supply Point (BSP). The lower voltage DN was originally designed to be passive and was not actively managed, with unidirectional power flow from the BSP, through the DN, to the load customer (Fig. 1). With the advent of greater levels of Distributed Generation (DG), this is now changing.

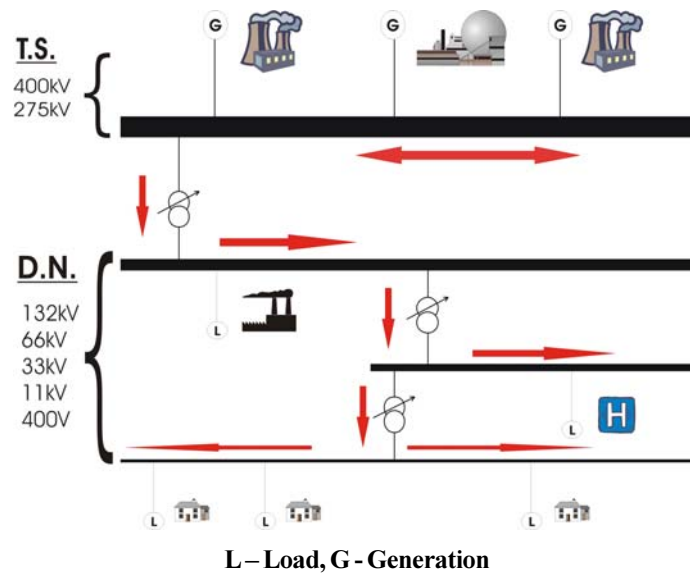


Fig. 1 Conventional Centralised Electricity System

When compared to centralised power plants connected to conventional large electricity systems, DG plant tends to be of lower capacity, distributed across the system, unconstrained and connected at lower voltages. At present, the majority of DG is being connected at Medium Voltage (MV), such as wind farms and CHP installations. Small Scale Embedded Generators (SSEG), for example domestic solar panels, fuels cells and Domestic Combined Heat and Power (dCHP) units, are situated in the home or small business premise and connected via a metering system to the DN. These SSEGs are connected at the extreme edges of the network and at the very lowest voltage, often single phase. SSEGs present the next step in a natural progression towards a fully dispersed generating system. If the future electricity system is to accommodate the expected growth in DG at lower voltages, particularly SSEG, it will need to change from a design standpoint, as well as a management and commercial perspective. (Fig. 2)

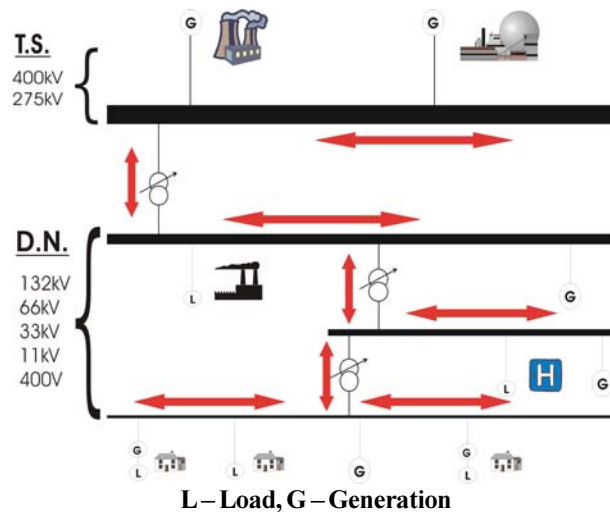


Fig. 2 Future Electrical System with DG and SSEG embedded in the DN

2. SSEG GROWTH AND ASSOCIATED CHARACTERISTICS

There is no universally agreed description of what defines an SSEG. For the purposes of this paper it will be considered to be systems producing an electrical output of 3kVA per phase or less at between 0.95 - 1.0 power factor. There are several different categories of SSEG either at market or under development and they are generally categorised based on the primary energy resource that they use.

The most common are:

- Photovoltaics (PV)
- Micro-wind
- Micro-hydro
- dCHP:
 - Internal Combustion Engine (ICE)
 - External Combustion Engine (ECE)
 - Fuel Cells (FCs)

Each of these categories of SSEG will have, to different extents, a contribution to make to the future make-up of the Asia electricity industry. The two main types of network connected SSEG which are beginning to gain a significant market foothold around the world are photovoltaics and dCHP [1, 2]. Network connected micro-wind and micro-hydro are very site specific and as such, are not expected to have a significant level of market penetration. In Asia, photovoltaics and dCHP are likely to have the most significant impact over the next 20 years. Some of the characteristics, potential benefits and disadvantages of each of these two emerging technologies are briefly outlined below:

2.1 Photovoltaics (PV)

At present, PV is probably the most mature and well understood of the two technologies and is already widely available on the market. They are installed and connected to the network in many countries, especially in Japan where they have the largest amount of installed PV in the world, with over 560MW of network connected distributed PV [1]. PV's relatively long payback periods of up to 20 years can still make it less economically attractive than some more conventional electricity sources. However, PV has many advantages including no on-going fuel costs and in warm, sunny climates they produce electricity when it is often in high demand in the home or office to meet air conditioning and refrigeration needs. As the technology becomes more mature, the average cost of PV installations per kWh is reducing considerably. In Japan the cost has approximately halved in the last 10 years (Fig. 3). In addition to the decreasing costs, government subsidies are also helping to promote the technology. As a consequence, the technology is becoming ever more attractive to consumers. In the US and Europe, the majority of PV capacity is typically on public facilities. In Japan, 80% of the installations are on private houses [3]. This has been aided by government initiatives and the routine network connection and net metering of PV in Japan.

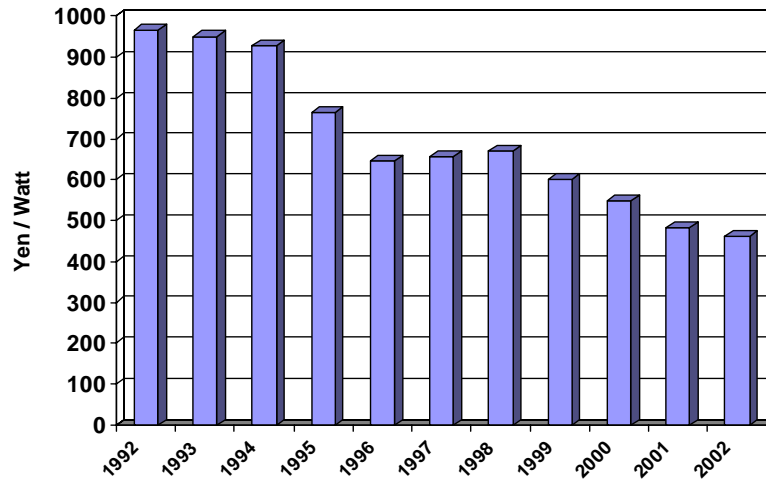


Fig. 3 Japan PV Module Prices in Yen per Watt Source: International Energy Agency [1]

2.2 dCHP

dCHP can roughly be split into three categories based on the prime mover of each technology. The output characteristics and basic information on each type of technology is summarised in Table 1:

Table 1 Types of dCHP and Basic Characteristics

	kWe	Ratio (kWe : kWt)	Total Efficiency	Fuel Type
ICE	1.5 – 5.5	1:2 – 1:3	80 – 90%	NG/LPG/Oil
ECE	1.0 – 3.0	1:3 – 1:8	90 - 95%	NG/Oil
Fuel Cells	1.0 – 5.0	1:1 – 1:3	~ 80%	NG

ICE dCHP units are available on the market at the moment and have been used where power flexibility is required. However, the high emissions from the exhaust and inherent noise levels caused by the fuel explosion in the chambers often make it unsuitable for domestic properties.

Considerable advances in the development of dCHP using the Stirling Engine ECE technology have resulted in domestic products which are due to be launched to the mass market in the next 1-2 years. Stirling engines are very efficient, quiet, compact and have low pollutant emissions compared to the ICE. The Stirling Engine has a high Thermal:Electrical ratio which has made it less attractive to the South East Asia market where high thermal output is often less desirable. It is however being highly promoted, particularly in North European countries where the climate is colder. It is for these reasons that many companies concerned with dCHP development see the Stirling Engine as a bridging technology moving from ICE towards Fuel Cells as Fig. 4 shows. [4, 5].

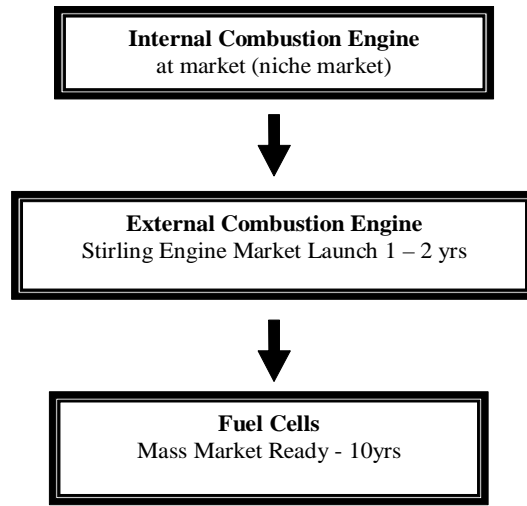


Fig.4 Evolving microCHP Engine Technology

Fuel Cells offer high efficiency, low emissions and very low noise levels. Natural Gas (NG) is reformed into hydrogen before being converted into electricity. The expansion of the NG network throughout Asia has added to the appeal of this technology. The Thermal:Electrical ratio for Fuel Cells is low which is beneficial in situations where heat for hot water or heating is not a high priority. Although a few Fuel Cells are available on the market at present, they are still expensive and hence are not expected to become mass market for another 5-15 years. However, both PV and FCs are expected to become significant contributors to the generating capacities of countries throughout Asia over the next 5-15 years. The effects of this increasing SSEG capacity on the DN will have to be fully understood to help identify any potential obstacles and to minimise their effect.

3. METHODOLOGY

3.1 Network Case Study

To study the effects of high levels of SSEG penetration on a Distribution Network (DN), a small town was identified with suitable population size, demographics, Natural Gas (NG) supply, consumer connection information, load data and network system data. The town chosen has approximately 1000 domestic and small business connections and a representative mix of industrial and residential load. The DN was modelled using a power systems simulation package and provided the study network for the research. System information including load records, network data, connection types and geographical data for the town and surrounding area was gathered and used to model the DN [6 - 8].

Fig. 5 shows a schematic of the network from the 33kV infeed transformer, to the 11kV network, through the 11/0.4kV transformers and down to the 400V busbar level. In Fig. 5, the main 11kV feeder supplying the town is boxed, and this accounts for approximately 50% of the load taken from the 33/11kV transformer based on max load figures. The remaining four 11kV feeders serve smaller, rural loads such as farms, isolated homes and small villages. The study deals primarily with the main 11kV feeder serving the town.

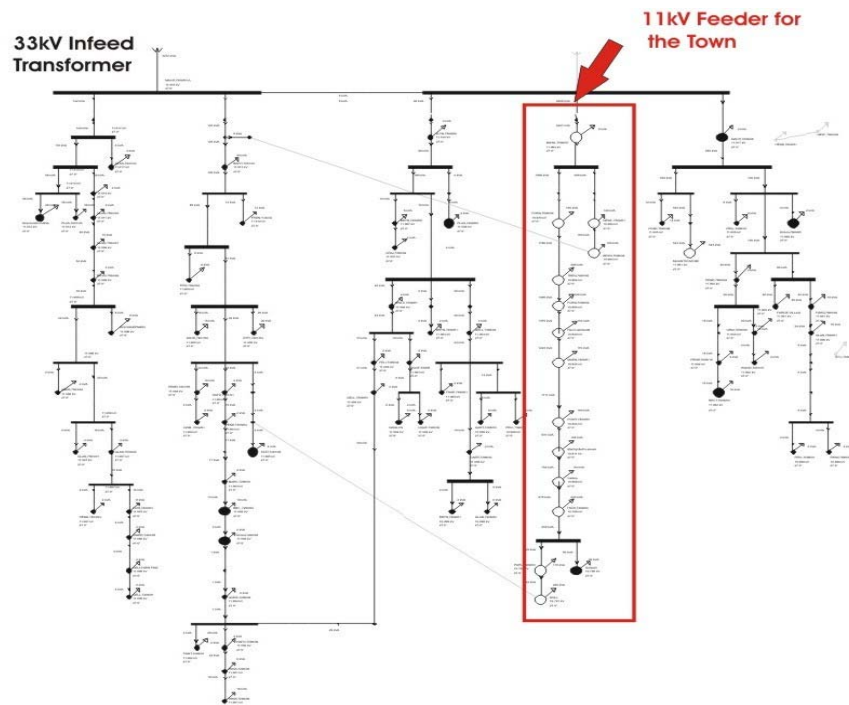


Fig. 5 11kV Network supplying the Town and Surrounding Area

3.2 Load Data

Half hourly load data was recorded at the 11kV busbar of the 33/11kV infeed transformer for 12 months. A summary of this data is shown in Table 2. The 12 month maximum load at each of the 11/0.4kV transformers was also recorded. The assumption was made that the Min : Max : Ave loads at the 11/0.4kV transformers would be approximately proportional to those at the 33/11kV transformer. From the 33/11kV transformer data, scaling factors were derived and used to produce profiles for the 11/0.4kV transformers based on the maximum recorded loads at the 11/0.4kV transformers.

Table 2 Summary of 12 months of 33/11kV Transformer Data

	S (MVA)	% of MAX	Scaling Factor	p.f.	P (MW)	Q (MVAr)
Max Reading	5.09	100%	~100%	0.987	5.02	0.83
Min Reading	1.03	20%	~20%	0.929	0.95	0.38
Average	2.50	49%	~50%	0.950	n/a	n/a

Table 3 shows the domestic connection figures and load data for all the transformers on the 11kV feeder that serves the town. These load figures were then used to create load profiles for all the 11/0.4kV transformers in the town. These matched the profile of the data recorded at the 33/11kV transformer and were similar in pattern to the Electricity Associations domestic profile shown in Fig. 6.

Table 3 Load Data at the 0.4kV busbar of the 11/0.4kV Transformer

11/0.4kV T-former Code	Number of Domestic Connections	1yr Max Recorded Load(kVA)	Min 20% (kVA)	40% (kVA)	Ave. 50% (kVA)	60% (kVA)	80% (kVA)	Max 100% (kVA)
A	0	6	1.2	2.4	3.0	3.6	4.8	6
B	79	140	28.0	56.0	70.0	84.0	112.0	140
C	184	160	32.0	64.0	80.0	96.0	128.0	160
D	39	160	32.0	64.0	80.0	96.0	128.0	160
E	144	280	56.0	112.0	140.0	168.0	224.0	280
F	68	120	24.0	48.0	60.0	72.0	96.0	120
G	68	152	30.4	60.8	76.0	91.2	121.6	152
H	50	110	22.0	44.0	55.0	66.0	88.0	110
I	96	180	36.0	72.0	90.0	108.0	144.0	180
J	0	168	33.6	67.2	84.0	100.8	134.4	168
K	32	84	16.8	33.6	42.0	50.4	67.2	84
L	0	220	44.0	88.0	110.0	132.0	176.0	220
M	141	170	34.0	68.0	85.0	102.0	136.0	170
N	112	240	48.0	96.0	120.0	144.0	192.0	240
O	10	50	10.0	20.0	25.0	30.0	40.0	50
<i>Total</i>	<i>1023</i>	<i>2240</i>	<i>448</i>	<i>896</i>	<i>1120</i>	<i>1344</i>	<i>1792</i>	<i>2240</i>

3.3 SSEG Generation Data

Domestic generation data was derived from the number of connections at the 400V level of the 11/0.4kV transformer multiplied by the capacity of each domestic generating unit. A range of SSEG capacities was used from 1kVA up to a maximum of 3kVA in steps of 1kVA. Power flow network simulations were carried out over the full 24 hour period at half hourly intervals for:

- a range of penetration levels,
- a range of SSEG unit capacities,
- a range of load levels,
- at 1 and 0.95 power factors leading and lagging.

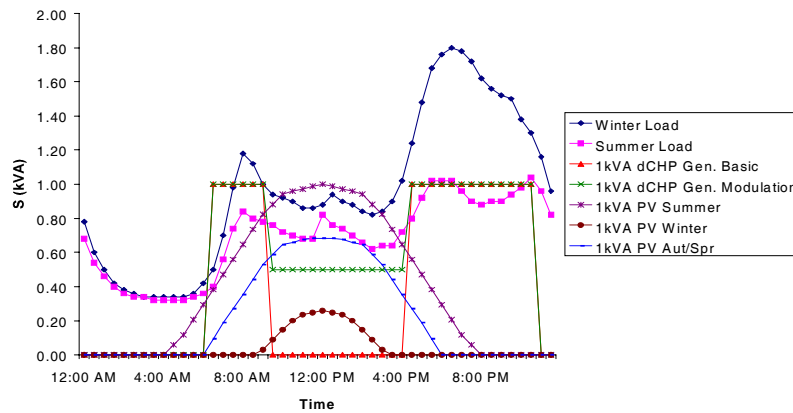


Fig.6 Typical Load and Generation Profiles

For these network simulations, an even spread of installations across the town's residential properties was assumed. Typical generating profiles for PV and dCHP were used as in Fig. 6 [9, 10]. For the purposes of this paper, it is assumed that all the SSEG units generate electricity at the same time corresponding to the profiles shown in Fig. 6, i.e. for a 10% penetration level, 102 generators were added evenly across the 1023 consumers on the network and all 102 generated at the same time matching the given profiles. All load and generation was aggregated and added to the model at the LV busbar of the 11/0.4kV transformer.

Simulations were also carried out for a number of circumstances that were not represented by the profile data described above. These included:

- Uneven spread of installations across the town.
- Concentrated installations as part of a housing estate upgrade.
- Untypical load/generation patterns (e.g. holidays, national events).

The main network simulation results were recorded including voltage, power flow and fault level. These were then analysed and a brief selection of some of the significant network events along the 11kV feeder, 11/0.4kV transformers and busbars is reported in the results section and discussed.

4. RESULTS AND DISCUSSION

Selections of results are given for the load / generation scenarios shown in Table 4. These represent a few of the key load / generation mixes where significant network events occurred. These scenarios are analysed for each of the 1, 2 and 3 kVA SSEG capacity sizes.

Table 4 Load and Generation Scenarios

Scenario	Description	Load % of max	SSEG % Penetration
A	Max Load, Zero Generation	100%	0%
B	Min Load, Zero Generation	20%	0%
C	Min Load, Max Gen	20%	100%
D	12:00noon (PV)/8:00am (dCHP)	50%	100%
E	Max Load 6:30pm	100%	100%

4.1 Power Flow

4.1.1 1kVA capacity SSEGs

For SSEGs of capacity 1kVA, the percentage of 11/0.4kV transformers experiencing reverse power flows for different load levels is shown in Fig. 7(a). It can be seen that at minimum load, reverse power flow does not occur until there is a 20% penetration level of SSEGs. As would be expected, the transformers which are first to experience reverse power flow are those which have a high proportion of domestic connections, e.g. transformers C and M. A rapid increase in the number of transformers experiencing reverse power flow occurs from 30 - 50% penetration when almost 70% of the transformers are under reverse power flow. Almost no reverse power flow occurs under 100% load conditions.

It is unlikely that a significant number of SSEGs will be exporting electricity onto the network when the load demand is at its lowest (20%) level at 4:00am. For this reason, reverse power flows are not anticipated to be significant problem for 1kVA SSEG units until penetration reaches levels

approaching 50%. It is at this level that some transformers start experiencing reverse power flows at certain times of the day, e.g. at 12:00noon for PV and 8:00am for dCHP.

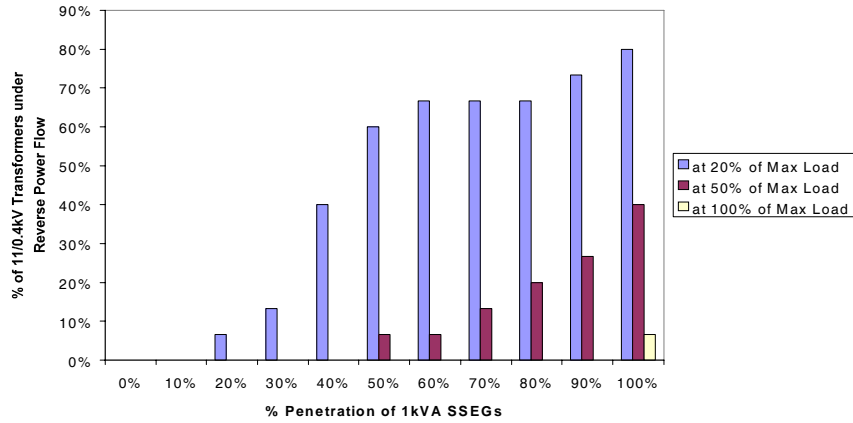


Fig. 7(a) Reverse Power Flows with 1kVA SSEG Units

4.1.2 2kVA capacity SSEGs

Fig. 7(b) shows that reverse power flow occurs at lower penetration levels for all three load levels shown compared with the 1kVA results. Most notably it can be seen that for 20% and 50% load levels, reverse power flows occur across a greater number of transformers at an earlier penetration level with reverse flows occurring at 30% penetration levels at 50% load levels, i.e. 8:00am and 12:00noon.

Even at the maximum 100% load conditions, some transformers experience reverse flows at penetration levels as low as 50%. This has significant implications; particularly in cases where there is an SSEG installation programme on a housing estate or for a specific area.

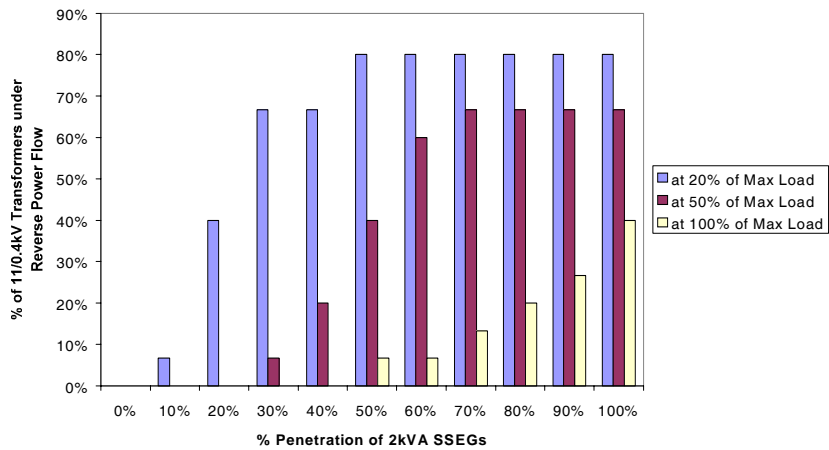


Fig. 7(b) Reverse Power Flows with 2kVA SSEG Units

4.1.3 3kVA capacity SSEGs

Fig. 7(c) again shows reverse flow happening at lower penetration levels for all three load levels. However, most notable here is the fact that there is a steep increase in the numbers of transformers undergoing reverse flow at an early stage. By 20% penetration reverse power flows are being experienced at both 20% and 50% loading. This is equivalent to 8:00am or 12noon on a standard day.

At 90% penetration levels, almost all of the transformers which have domestic connections are experiencing reverse power flows. Again this has implications for areas where widespread SSEG installations are being considered.

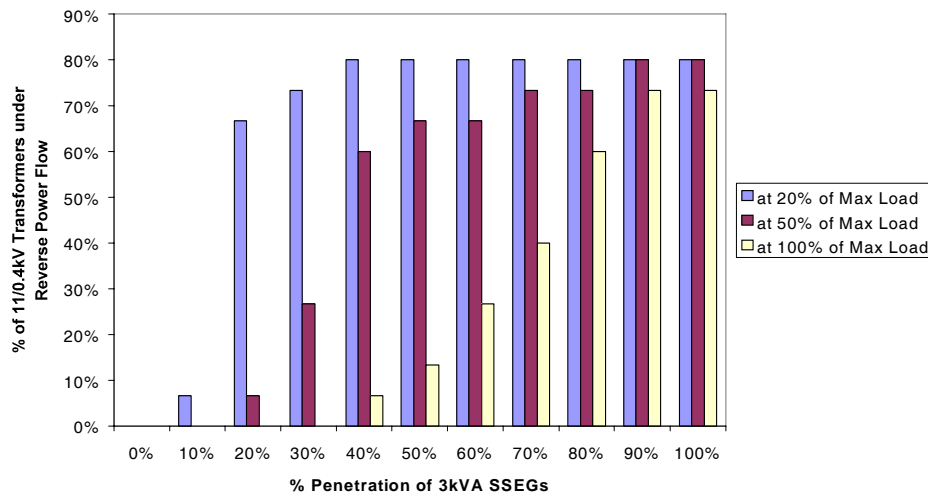


Fig. 7(c) Reverse Power Flows with 3kVA SSEG Units

4.1.4 11kV Town Feeder

Reverse power flows occurred along the town feeder at the following penetration levels as summarised in Table 5. At these points the 11kV town feeder started to export electricity to the 11kV busbar of the 33/11kV transformer, rather than being a net importer of electricity.

Table 5 Penetration Levels at which the 11kV Town Feeder begins to Export

SSEG Unit capacity	% of Max Load		
	20	50	100
1kVA	50	N/E	N/E
2kVA	30	60	N/E
3kVA	20	40	80

N/E – No Export occurred

It can be seen that it is unlikely that 1kVA units will ever cause the feeder to become an exporter of electricity. However, as SSEG unit capacity sizes increase, the penetration levels at which the feeder may be an exporter of electricity lowers. For example for 3kVA units, a 40% penetration of SSEGs across the town will cause the feeder to become an exporter at 50% load. This is equivalent to 8:00am in the morning for dCHP.

4.2 Voltage Variation

The 0.4kV busbars at each of the 11/0.4kV transformers were studied and the voltage changes of four of the busbars are shown in Fig. 8(a), (b), and (c). The selection of results shown correspond to busbars C, F, J and M for each of the scenarios in Table 4, at 100% penetration of SSEG for the unit capacities 1, 2, 3kVA.

4.2.1 1kVA SSEG

It can be seen that for busbar M, there is a 6.5% voltage rise between maximum load conditions with no generation (scenario A), to minimum load conditions with maximum generation (scenario C). This compares to a voltage range of only 3.9% without SSEG.

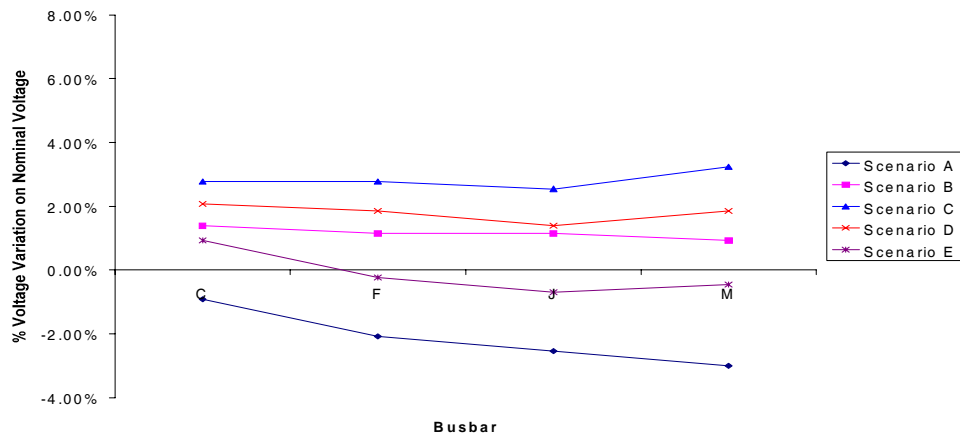


Fig. 8(a) Voltage Variation at Selected 0.4kV busbars for 1kVA units

4.2.2 2kVA SSEG

Fig. 8(b) shows an 8.5% voltage rise at the 0.4kV busbar M between scenario A and C compared to a voltage rise of 3.9% between max and min load conditions for no SSEG.

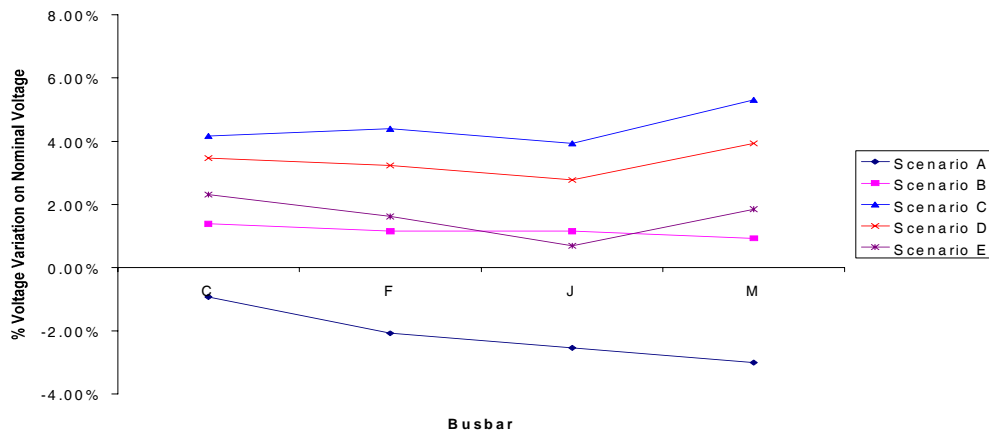


Fig. 8(b) Voltage Variation at Selected 0.4kV busbars for 2kVA units

4.2.3 3kVA SSEG

As expected, the 3kVA SSEG units represented in Fig. 8(c) show the biggest rise in voltage. For 0.4kV busbar M, the voltage rise between scenario A and C is over 10%.

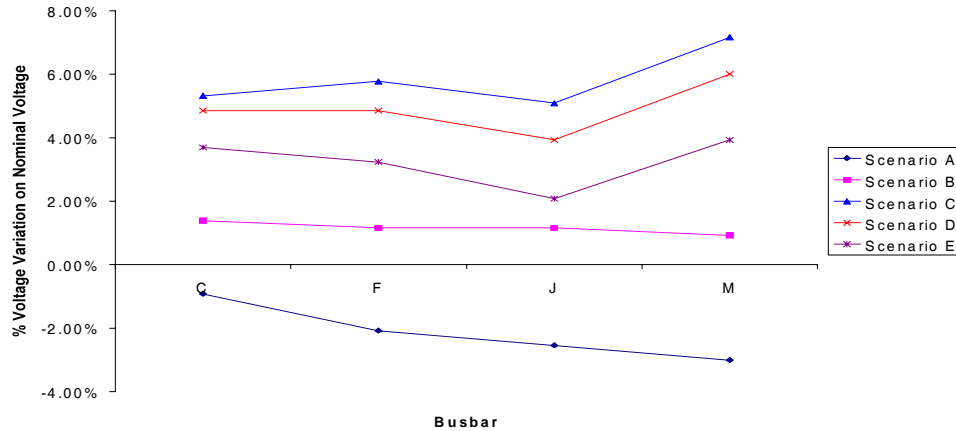


Fig. 8(c) Voltage Variation at Selected 0.4kV busbars for 3kVA units

A 10% swing in voltage levels between the different scenarios is significant, being over 2.5 times that of the voltage range without any SSEG. However it is still generally within the voltage bandwidth allowed by most DN operators. However, these results do not take into account the voltage rise between the 0.4kV busbar and the customer supply point. Preliminary models of this section of the DN show that substantial voltage rises caused by SSEG occur, due primarily to the higher R/X ratio of the consumer feeder cable. This will further broaden the voltage ranges discussed above, causing voltage violations on a widespread scale throughout the network, particularly for higher capacity SSEG units. Work is ongoing to further quantify these likely levels and derive 'rules of thumb' for LV design guidelines.

5. CONCLUSIONS

Reverse power flow is not anticipated to be a major problem for lower SSEG capacities of around 1kVA. However, as SSEG unit capacities increase towards 3kVA, reverse power flow across a large number of transformers, and along the main 11kV feeder, will become a significant issue at lower penetration levels. At 3kVA, a 40% penetration of SSEG across the town will cause the main town feeder to become an exporter of electricity at 50% load conditions.

SSEG will cause significant disruption to voltage levels of the LV network at penetration levels of 30%. As SSEG technology becomes more mature and unit sizes increase from the estimated initial market size of approximately 1-1.5kVA to 2.5-3.0 kVA, major voltage swings and voltage violations will become likely on the LV DN at relatively low penetration levels of 30%.

In real systems LV transformers are usually set with the LV tap of the transformer set well above the nominal voltage for no load conditions. This is to compensate for voltage drop when load is added. This is a design legacy from when LV networks supported loads only and no generation. In this situation, over voltage violations from increased SSEG will occur much sooner than the above results would suggest. Work is also being carried out to quantify these conditions.

Possible solutions to the anticipated voltage level problems discussed above include resetting taps on transformers where mechanically feasible, loosening tolerance levels on LV voltage levels and active management of the network down to the LV level. However, it should be noted that because of the greater volume of equipment and units at the LV level, any solution requiring physical intervention or on-going information management may prove too expensive.

6. ACKNOWLEDGEMENTS

The authors would like to thank SP Power Systems Ltd for their help and collaborations with this research.

7. REFERENCES

- [1] International Energy Agency. 2003. Trends in Photovoltaic Applications – Survey report of selected IEA countries between 1992 and 2002. Paris, IEA.
- [2] Sharpe, L. 2003. Swap your boiler for a power station. *The IEE Review* 49(8): 24-25.
- [3] WCPEC-3 “Citizens’ work in Japan” international conference working committee. 2003. Citizens work on the spread of photovoltaic energy in Japan. In *Proceedings of the 3rd World Convention on Photovoltaic Energy Conversion (WCPEC-3)*. Osaka, 11-18 May.
- [4] Stares, I. 2003. Baxi Group - dCHP Business Development. In *Proceedings of SBGI Seminar on Domestic CHP*. London, 9 July, SBGI.
- [5] Burton, S. 2003. MicroCHP - A Global View. In *Proceedings of SBGI Seminar on Domestic CHP*. London, 9 July, SBGI/FaberMaunsell.
- [6] SP Power Systems Limited. 2002. *SP Distribution Network Design Manual - Network Design Principles*. Glasgow, Scottish Power plc.
- [7] Lakervi, E. and Holmes, E.J. 2003. *Electricity Distribution Network Design*. 2nd edition (revised), London, Institution of Electrical Engineers.
- [8] Weedy, B. M. and Cory, B. J. 1998. *Electric Power Systems*. 4th edition, London: John Wiley and Sons.
- [9] Twidell, J. and Weir, T. 1997. *Renewable Energy Resources*. 1st edition (revised), London, E & F.N. Spon.
- [10] WhisperGen Ltd. 2003. AC WhisperGen System - Product Specification. Christchurch, Whisper Tech Ltd.