IMPROVED CHARACTERISATION OF EMBEDDED PV GENERATION ON THE LV NETWORK

Jorge ACOSTA
TNEI Services – UK
jorge.acosta@tnei.co.uk

Russ BRYANS
TNEI Services – UK
russ.bryans@tnei.co.uk

Charlotte HIGGINS
TNEI Services - UK
charlotte.higgins@tnei.co.uk

Sarah WEATHERHEAD
TNEI Services – UK
sarah.weatherhead@tnei.co.uk

Alan COLLINSON
Scottish Power Energy Networks – UK
alan.collinson@sppowersystems.com

ABSTRACT

The modelling of LV networks with high uptake of distributed generation (e.g. solar PV) has become a topic of high interest in the academic community and the industry recently as PV uptake has increased through provision of attractive government incentive schemes. The effect that PV generators will have on LV network voltage and load, which may be highly transient, are not well characterised due to limited monitoring at LV to date. High uptake of PV coincident with low demand can lead to the voltage statutory limits being exceeded towards the ends of LV feeders.

A simple, representative approach has been developed and validated with detailed network monitoring data and modelling for characterising PV behaviour and estimating generation connection capacity. This is invaluable for assessing large volumes of LV network.

INTRODUCTION

Scottish Power Energy Networks (SPEN) and TNEI are collaborating on the Low Carbon Network Fund innovation project 'Flexible Networks for a Low Carbon Future' which has included installing detailed LV monitoring on secondary substation LV feeders at three trial network sites within the SPEN license areas. One of these trial sites in Wrexham, Wales has a high residential PV uptake due to a local council initiative.

In order to improve our understanding of the characteristics of an LV network with high PV, the objectives of this study were to;

- Develop a simple resource model for PV generation based on measured solar irradiance.
- Gain an understanding of typical load characteristics during times of peak PV generation by analysing monitoring data from an area of LV network containing feeders with both high and low PV uptake.
- Build a power systems network model of Ruabon and verify with measured data.
- Determine the remaining generation capacity headroom at Ruabon.
- Provide recommendations on the future installation of small-scale PV schemes in the SP Manweb network.
- Provide more general learning on how to efficiently assess the impact of embedded PV generation on LV networks.

MODELLING OF PV GENERATION

PV Generation Resource Model

Maximum, minimum, average and standard deviation of solar irradiance was measured with a resolution of 5 minutes at the Ruabon primary substation.

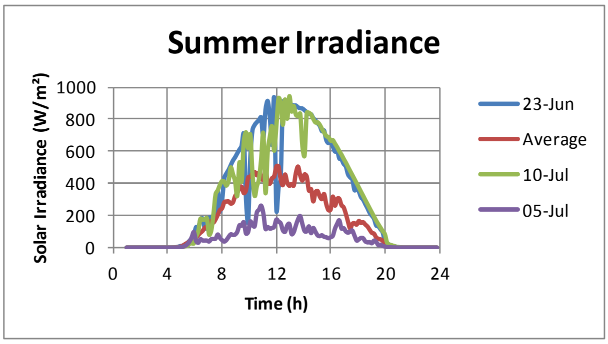

Figure 1 Ruabon Solar Irradiance for High and Low Irradiance Days

The solar irradiance measurement of the weather station is correlated with PV generation power output in the vicinity. Typically the rated power output of a PV installation is reached at 1000 W/m^2 irradiance [1].

The average solar irradiance for high and low solar irradiance days is plotted in Figure 1 with the average irradiance shown for the representative summer months analysed (June/July 2014) also shown, having a peak of 450 W/m^2. The high solar irradiance days have a peak irradiance of 900 W/m^2. Average 5 minute solar irradiance was used for modelling. Maximum 5 minute irradiance may last for only very brief periods and would give a more conservative representation of PV generation.

Solar Irradiance Distribution

Figure 2 shows the annual average and maximum solar irradiance distribution for 2013/2104. It can be appreciated that the solar irradiance exceeded 900 W/m^2 for only about 5 hours in total for average irradiance and higher for maximum irradiance. However, these instances when solar irradiance goes above 900 W/m^2 are sporadic and isolated occurrences. Thus, the probability of achieving sustained rated power output and during feeder demand conditions that would result in voltage exceeding statutory limits is very small for Ruabon.

It should be noted that solar irradiance can increase above 1000W/m^2 briefly due to refraction from passing of clouds, obstacles, pollution etc.

The WPD PV FiT metering analysis study found that for small-scale PV installations, the average (median) proportion of actual to potential output was 44% and the proportion of greater than 70% of potential output was extremely low (<0.01%). Our findings align with this learning outcome [2].

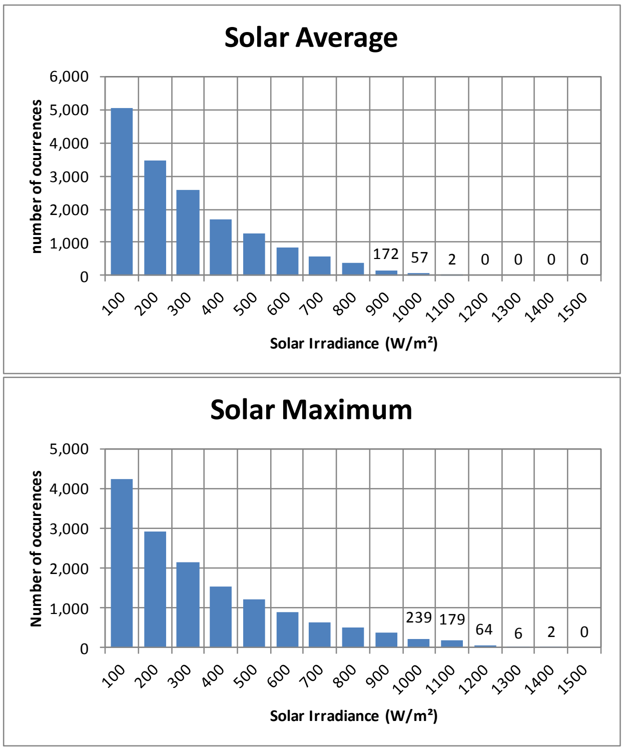

Figure 2. Distribution of Measured Average and Maximum Solar Irradiance at Ruabon

Typical Load Characteristics

Measured phase voltage and current at a 10-minute resolution was available for all LV feeders connected to the secondary substations in the Ruabon LV network. Load data was analysed from the 18th of June 2013 to the 28th of July 2014. The months of June and July 2014 were selected as representative of the highest solar irradiance and lowest network demand; generally experienced during the UK summer. The apparent power was calculated using the three single phase currents for every feeder and voltage (voltage across phases was found not to vary significantly). This three phase measured power output was to be compared with the network model results.

The selected LV feeders considered to characterise typical minimum demand profiles are Maple Drive (MD) and Hamden Arm Link box (HALB) connected to Plas Madoc secondary substation. The Maple Drive feeder contains 3.7 kWp of installed PV and 26 customers (142 W/customer). Hampden Arms link box feeder contains 20.6 kWp of installed PV, however there are 94 customers so PV generation per customer is still fairly low (<220 W/customer). These LV feeders with low PV uptake were selected to minimise the effect of PV generation on average daily load profile during summer.

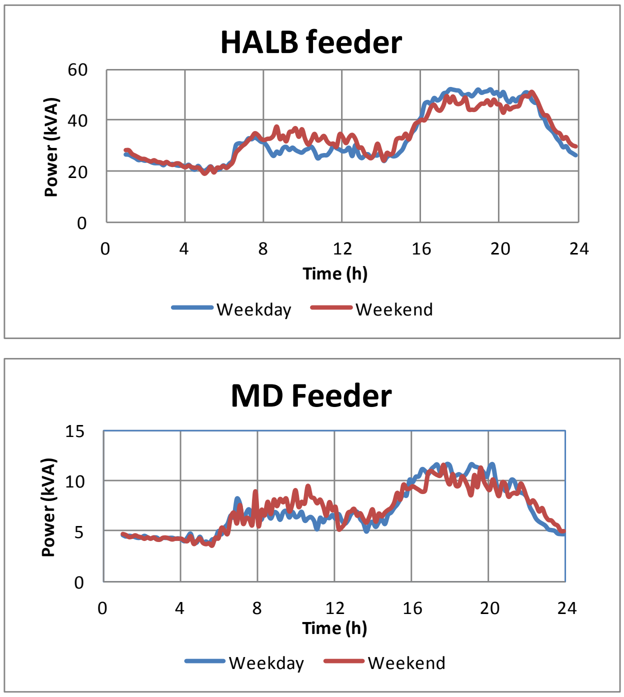

Figure 3 Selected LV Feeder Average Summer Load Profile

The measured average minimum demand profiles for weekdays and weekends over the summer period (June/July) are shown in Figure 3. Customer behaviour over weekdays and weekends can be seen to vary. For weekdays, demand is lower during the day and the evening peak is slightly higher compared to the weekend. This indicates that PV generation will have the most impact on feeder voltage and loading during a weekday when demand is generally lower during the day.

The minimum demand profile was normalised in per unit based on the number of LV domestic customers to enable application to other LV feeders. The average daily peak demand for the summer was calculated to be approximately 555 W per customer. The generic minimum demand profile used in the network model is shown in Figure 4.

This profile is assumed to be representative of LV feeders with residential properties and minimal PV across the Ruabon network. It does not consider socio-economic differences between customers that may cause demand variation or the interrelated effect on demand of different housing stock.

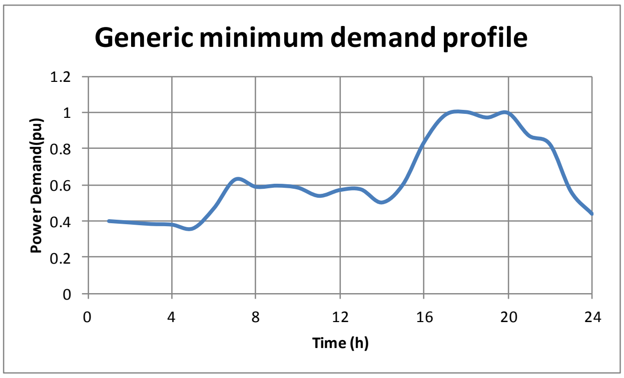

Figure 4 Generic Minimum Demand Profile

LV Network Modelling

A power systems model of part of the Ruabon LV network was constructed in IPSA2 power systems software. This is a radially operated LV network with some capacity to be run interconnected. Seven secondary substations, Peris, Plas Madoc, Dinas, Idwal, Hampden Way, Bodlyn and Leisure centre, were modelled with their respective LV feeders. Conductor length, type and material data was provided by SPEN with very little missing data. In the limited cases where data was not available, cable type was assumed based on the surrounding cables. The number of LV customers and PV installations along with average rated generation capacity were defined in the LV network model, as recorded in the SPEN GIS database.
A three phase LV network was modelled; individual phases were not represented.

LV Load Modelling

Domestic demand and PV generation were aggregated along LV feeders in the network model in order to simplify the analysis. Typically between 2 to 4 lumped loads were modelled depending on the length of the cable. This enables an efficient network modelling approach without compromising accuracy. The generation was added to the demand by assuming it to be a negative load offsetting the demand.
The total rated PV generation in each aggregated load was calculated based on the number of installations. This was added to the appropriate LV feeder using an average rated maximum generation of 1.6 kW per installation and power output defined by the measured solar irradiance throughout the day. A value of 1.6 kW was found to provide a good representation of the limited range of PV generation rated capacity within the Ruabon LV network.
LV feeders with commercial and industrial customers were not modelled. PV generation in Ruabon is generally due to domestic customer connections.
Customer demand was based on the generic minimum demand profile and number of customers along the feeder.

Model Validation

Two high irradiance days were selected for model validation and analysis. Validation results are shown in Figure 5 for 2 of the 27 LV feeders analysed and show good correlation of PV generation and demand behaviour.

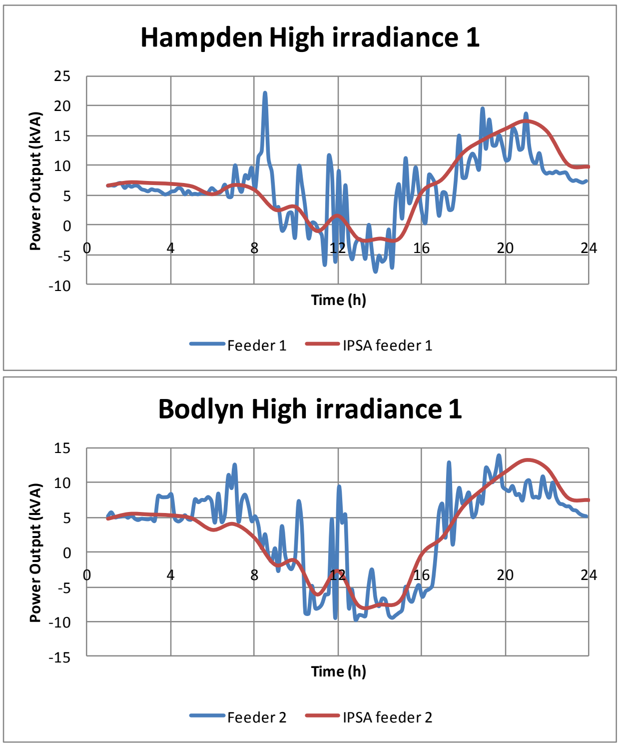

Figure 5 Feeder validation

Table 1 shows the range of correlation coefficients achieved for comparison of modelled and measured feeder power output.

Table 1 – needs to be properly formatted

No. of LV Feeders	Correlation Coefficient
11	>0.8 High
12	>0.5 medium
4	<0.5

The validation process demonstrated that the model is fairly robust and can be used confidently to assess the voltage profile and impact of the PV across the Ruabon network and other similar LV networks. It also suggests that the generic minimum demand profile and measured solar irradiance data could be used with a simple LV feeder model, in the absence of more detailed network modelling, to estimate the voltage profile.

PROBABILISTIC CHARACTERISATION OF LV NETWORK VOLTAGE

The distribution of voltage measurements over the summer period for secondary substations in the Ruabon LV network provides an insight into network behaviour when PV generation is highest. Figure **6** shows Dinas secondary substation voltage distribution for all three phases over June and July 2014. Voltage only exceeds the statutory limit for a total of about three hours during this period. Thus, for over 99.9% of the time, the voltage was acceptable for Dinas secondary substation.

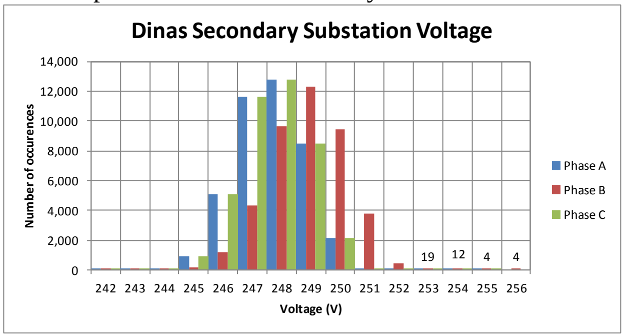

Figure 6. Voltage Distribution at Dinas Secondary substation

These excursions are likely due to sudden loss of load with network fault or voltage change further up network (at HV). Results for all other secondary substations are broadly similar. Peris secondary substation was always within the statutory voltage limits due to the transformer tap.

GENERATION HEADROOM AT RUABON

An assessment was made of the available generation headroom at Ruabon based on the validated network model. Plas Madoc Feeder 1 (with no PV installed), Plas Madoc Feeder 3 and Dinas Feeder 1 (medium PV uptake), and Idwal Feeder 4 (with high PV uptake) were analysed in detail to assess feeder voltage rise for a range of PV uptake higher than present. Generation headroom available was determined by reviewing the resultant voltage profiles in relation to the statutory voltage limits (+6% and -10% on 240 V for the LV network).

Scenarios analysed

Using the IPSA network model, four scenarios were defined and modelled as follows;

- Scenario 1: High irradiance day 2, installed and prospective PV
- Scenario 2: High irradiance day 2, installed and prospective PV with increased output by 20%
-Scenario 3: High irradiance day 2, installed and prospective PV with increased output by 30%
- Scenario 4: High irradiance day 2, installed and prospective PV and a 3% decrease in primary substation voltage
- Scenario 5: High irradiance day 2 installed and prospective PV and a 6% decrease in primary substation voltage.

Scenario 1 explores the impact of connection of the prospective PV to the network. Scenarios 2 and 3 investigate the impact of an increase of 20% and 30% in PV generation volumes (installed and prospective) respectively. Scenarios 4 and 5 explore the effect of reducing the primary substation voltage in steps of 3% (-3% and -6%, respectively) according to National Grid requirements for UK DNOs.

Results

Figure 7 to Figure 11 provide results for the voltage profile at the end of the LV feeders where it is expected to be highest due to PV uptake, for Scenarios 1, 2, 3, 4 and 5. The statutory voltage upper limit is represented by the dotted red line at 253 V.

It can be appreciated that the LV feeders with PV uptake experience some voltage rise at peak solar irradiance in the middle of the day and all LV feeders experience voltage drop in the late afternoon/evening at peak demand times. For the Idwal LV feeder with high PV uptake, the voltage rise is higher compared to the LV feeders with medium PV uptake, whereas the Plas Madoc LV feeder with no PV experiences minimal voltage rise. The voltage only exceeds statutory limits for Scenario 6, the highest PV uptake forecast, at the end of the high PV uptake LV feeder and this is marginal (253.1 V).

This indicates that the prospective PV generation and up to 30% additional PV generation can be connected in the Ruabon LV network without exceeding statutory voltage limits. This equates to approximately 50% total uptake. However, a physical limitation i.e. all rooftops already have PV panels installed would probably be reached for high uptake LV feeders before this 30% could be achieved due to PV clustering in some locations.

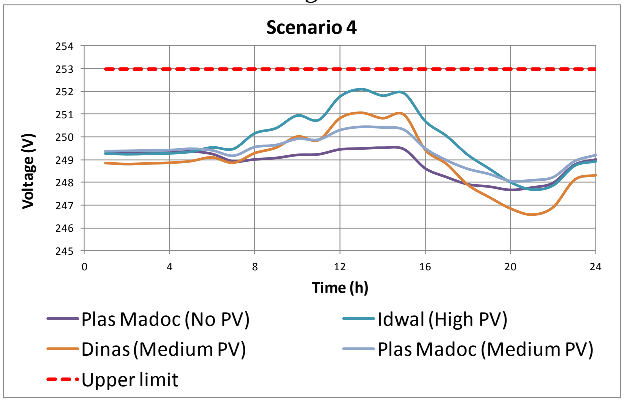

Figure 7. Voltage Profile for Scenario 4

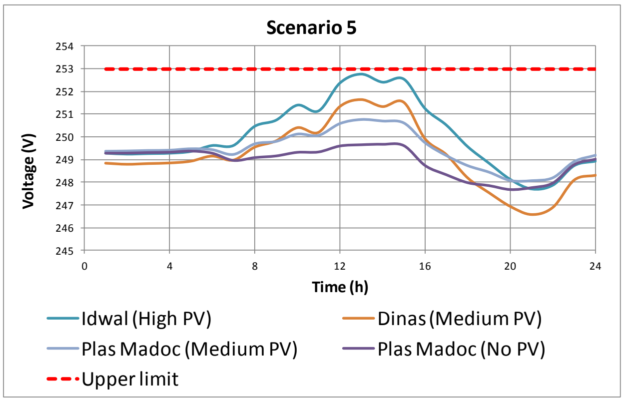

Figure 8. Voltage Profile for Scenario 5

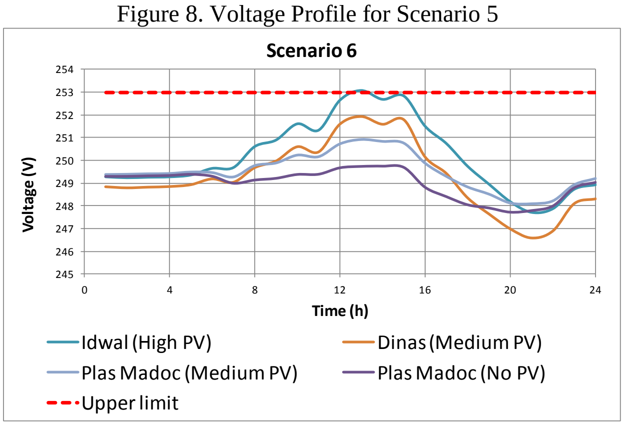

Figure 9 Voltage Profile for Scenario 6

Typically highly urban distribution networks are able to absorb high levels of distributed generation without causing voltage problems due to the higher demand and the limited space for small-scale installations. On the other hand rural distribution networks are less able to accept distributed generation due to the lower demand and larger space available for generator installation, which can cause higher voltages at the end of the feeders [3]. The Ruabon network is considered to generally be a suburban area with medium availability of PV uptake and limited space for small-scale generation installation due to residential loading.

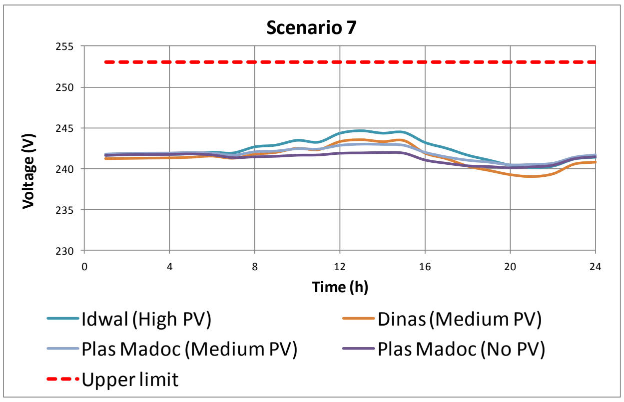

Figure 10.Voltage Profile for Scenario 7

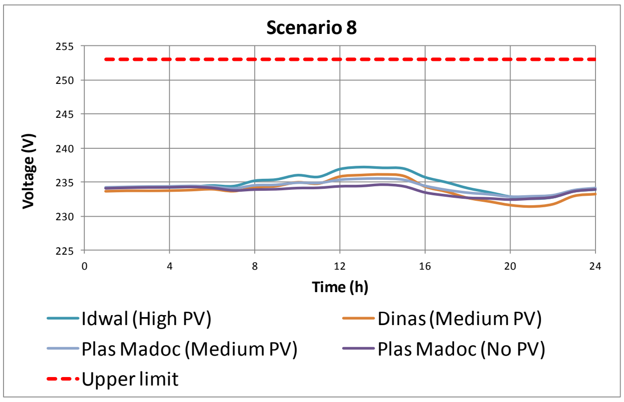

Figure 11. Voltage Profile for Scenario 8

CONCLUSIONS

A verified methodology has been developed comprising a simple PV resource assessment model (based on available solar irradiance data) and a generic normalised minimum demand profile for domestic customers. These could be input into a simple LV feeder model to estimate voltage at LV feeder end with increasing PV uptake on a suburban feeder with domestic customers.
A total average uptake of up to approximately 35% of PV generation can be installed on the Ruabon LV network before voltage management techniques need to be considered. Some of this uptake is clustered. Voltage reduction can be applied through network primaries to enable more PV to connect as long as this is proven not to cause any adverse effects for HV connected customers. Rural feeders would experience voltage rise issues earlier than suburban LV feeders at comparable PV uptakes.

REFERENCES

[1] British Standard (EN/IEC) 60904-3:2008 “Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data”
[2] Western Power Distribution, “Low voltage network templates,” Final report, UK.
[3] J.L. Acosta, Micro and Small-scale Generation in Urban Distribution Networks, PhD Thesis, School of Engineering, The University of Edinburgh, UK, 2012