MEASUREMENTS OF POWER QUALITY AND VOLTAGE LEVEL EFFECTS ASSOCIATED WITH A PHOTO VOLTAIC CLUSTER ON A DOMESTIC HOUSING ESTATE.

Paul Wright	Geoff Murphy	Ken Lennon	Paul Clarkson
National Physical Laboratory - UK	Scottish Power Energy Networks - UK	Scottish Power Energy Networks - UK	National Physical Laboratory - UK
paul.wright@npl.co.uk	geoff.murphy@sppowersystems.com	ken.lennon@sppowersystems.com	paul.clarkson@npl.co.uk

ABSTRACT

The power quality impact of a cluster of retro-fitted photovoltaic (PV) units on the local low voltage distribution network is investigated. A description is given of the network, PV installation and the measurement equipment used. Results are presented showing the effects of the PV installation on voltage level and other power quality parameters.

INTRODUCTION

The drive to reduce CO_2 emissions and meet various international targets, has led to an unprecedented level of connection of PV solar panel systems to the electricity supply system. In the UK the “feed-in tariff” pays a guaranteed price per unit of generated electricity to consumers who install photovoltaic panels on the roofs of domestic premises allowing predictable payback periods for the installation to be calculated. Various government grants and community schemes have further fuelled a rush to retrofit this technology.

The effect on the electricity supply system has been a secondary consideration of this governmental action and Distribution Network Operators (DNOs) are responsible for ensuring that clusters of PV can be accommodated without detrimental effects to the energy supply power quality such that electricity safety, quality and continuity regulations are met.

Hence there is an interest in the effect of PV on the network such that DNOs can predict the effect of planned large scale installations and if necessary make provisions for network reinforcements to mitigate any detrimental effects they have on power quality or network reliability.

In order to determine the effects of large-scale PV installations, the most reliable method is to undertake a measurement survey over a period of some weeks. This period should encompass a wide variation in weather conditions such that comparisons of the network behaviour with and without PV generation can be compared. This paper will report the details and finding of one such measurement survey.

DESCRIPTION OF THE INSTALLATION AND NETWORK CONFIGURATION

The measurement survey was conducted in the Summer of 2011 on “The Pencraig estate” on the Isle of Anglesey in North Wales. This estate is characterized by a high proportion of PV systems retrofitted to two-story domestic dwellings.

The study took place on low voltage (LV) feeder from the MV/LV substation in the north of the estate. The feeder comprises of a three phase main cable that is run radially out of the “North” substation to an underground link box that provides a *normally open point* (NOP). The feeder supplies 62 properties with a single phase connection and of these connections 49 include properties that each incorporate a 1.5 kW PV installation. Further measurements were made at the NOP “Mid Point” and at the “South” substation feeding the adjacent feeder at the NOP point.

The exact phasing of the PV connections is unknown however from the results it can be inferred that the distribution between the three phases in uneven and is approximately distributed 40%:40%:20% across phases L1:L2:L3.

MEASUREMENT APPARATUS

The measurement equipment used in the north substation has been recently built for high precision, high sampling rate (25.6 kHz) power and PQ measurements [1]. This instrument was configured to measure three phase: Vrms, Irms, Phase, active + reactive power, voltage unbalance, voltage harmonics and flicker.

The voltage measurement connections were made on the substation transformer secondary fuse board using fused crocodile clips. Flexible Rogowski coils were used to measure the three phase currents on the feeder main fuses.

The south and mid points were monitored using commercial PQ logging equipment at measurement rates of one average value per 5 minutes and 10 minutes respectively. Parameters were Vrms, Irms, phase, active + reactive power on three and one phase respectively.

MEASUREMENT RESULTS AND ANALYSIS

A considerable amount of data was collected during these surveys which were conducted from May 2011 until October 2011. The graphs and finding presented in this section are for selected periods only; generally chosen for relatively high PV generation associated with high solar radiation intermixed with period of poor weather such that comparisons can be made.

Active and Reactive Power

It is instructive to consider the power flow at the monitoring points over a period of time when the PV systems are receiving variable exposure to the sun.

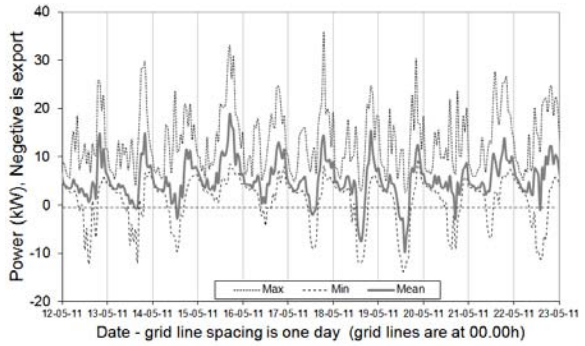

Fig.1, L2 Feeder Power; Max, Min and mean values for each hour are plotted.

Fig.1 shows a plot of the north substation L2 phase power vs. time for 10 days in May 2011. The time axis grid has a spacing of one day with the vertical line being 00.00h on a given day. Three traces are shown for the hourly maximum, minimum and average power respectively. Negative powers are associated with net energy export/generation from the PV systems.

The minimum plot (bottom trace) is interesting when negative, in that it gives some indication of the level of power export associated with PV generation. Generation occurs daily centred around 12h as would be expected. For the L2 phase results shown in Fig.2, there is a shift at the most negative extreme relative to the prevailing level of the middle average trace, of about 15 kW. This is assumed to be the approximate PV generation associated with the 20 times 1.5 kW PV units on the L2 phase. This implies the PV units are only generating at slightly over half capacity. Similar results are available for L1 and L3.

Variations in the minimum plot on a daily basis have been correlated with weather data. It should be noted that the PV gives some reasonable generation on most days.

Similar reactive power plots (not shown) are not strongly correlated to solar generation as PV panels/inverter systems are only providing the active power during periods of generation. As the reactive power for loads still needs to be supplied, it is left to the network to generate this wattless power for no revenue return. Aggregation of PV and other inverter generation on the network will leave an ever-increasing burden on network operators to generate the reactive power to satisfy the load.

Voltage Level

There is a presumption that voltage will rise during periods of PV generation. By measuring voltages in the three locations on the feeder, changes in the voltage level with generation can be investigated. However, there is some difficulty in observing generation related voltage level changes, as they are obscured by voltage regulation tap changes made by the network operator in order to maintain the voltage level within statutory limits. For this reason it is more beneficial to examine data at the 24h level.

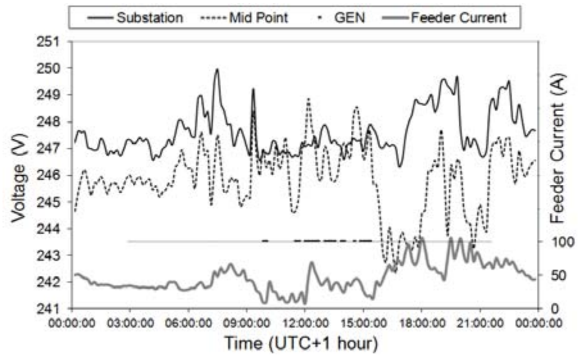

Fig.2, Feeder Voltages (LH axis) and current (RH axis) 18/05/11. Blacks dots indicate periods of PV generation.

Fig.2 shows several plots against time over a 24h period on a sunny day, 18/05/11; the two voltage measurements at the north and middle points are plotted against the left hand y-axis. The lower trace shows the current flowing into/out-of the feeder and is plotted on the right hand y-axis. To interpret the plots relative to PV behaviour, it is useful to identify periods of net energy export associated with PV generation. Energy export is shown in Fig.2 by the presence of the horizontal black dots used to indicate times when the PV is generating (as determined by a reversal of phase at the north sub-station).

All of the measurements taken have to be interpreted against a background of voltage regulation tap changes by the network operator. An example of a tap change of about 3 V can be seen between 20h and 22h in Fig.2. Unfortunately there is no information available as to the time and voltage level of these network control interventions.

The dotted trace is the feeder mid-point voltage; it can be seen that this trace is generally lower than the substation voltage trace due to the voltage drop along the feeder. During periods of high current load (17h to 18h) the feeder mid-point voltage is at the highest difference (about –4 V) from the substation voltage. However, during periods of PV generation (e.g. 1230h) the voltage at the mid-point rises above the substation voltage (by a maximum of about +1 V).

These measurements suggest that when comparing periods of high load and PV generation there is a rise in voltage at the mid-point compared with the substation transformer of about 4 V. In addition to this there is a further rise at secondary of the substation transformer of about 1 V associated with PV generation. As the voltage is at the high end of the statutory limits on this network (as is typical in the UK), such voltage rise maybe of some concern to the DNOs when planning to connect substantial amounts of PV.

It is instructive to visualize the rise in voltage due to PV generation compared to no generation. Using the high measurement rate (one minute) North data, the voltage measurements when the PV is generating were separated from the voltage measurements when there is no generation. For this purpose, generation is designated as measurements where the phase angle is beyond 90 degrees.

These two voltage measurement series (generating and not generating) are each plotted against time as shown in Fig.3 using light and dark grey data markers. The lighter grey marker represents non-generating; the darker grey marker represents generating.

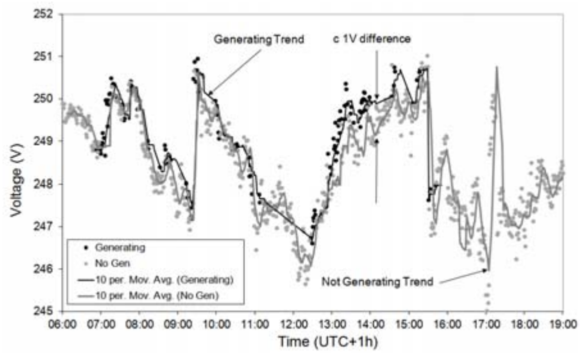

Fig.3, North substation voltage measurements separated into times when generating and times when not generating.

Two 10 minute moving average trend lines is added to the plot as shown by the solid lines, one for the generating markers (dark) and one for the non-generating (lighter). These trend lines can be used to visualize changes in the prevailing substation voltage. This technique is most instructive on a day when the sky is covered with broken cloud and the sun comes in and out of cloud cover repeatedly.

It should be noted with caution that at certain times when there is no generation, the trend line will move in a straight line through a period of no data to reach the next cluster of data. An example of this behaviour can be seen between approx. 11h and 12.30h. Also note the voltage discontinuity associated with network tap changes shortly after 09h, 15.30h and 17h.

The vertical difference between the solid trend lines gives some indication of the voltage rise due to PV generation at the substation transformer. In this case the rise was between 0.5 V and 1 V can be seen particularly well between 13h and 15h when there was probably sporadic sunshine and cloud.

Neither Fig.2 nor Fig.3 gives any indication of the voltage rise as a function of the magnitude of generated power. Fig.4 attempts to relate the change in voltage to the level of exported power at the north substation. Similar plots are used in the work described in [2].

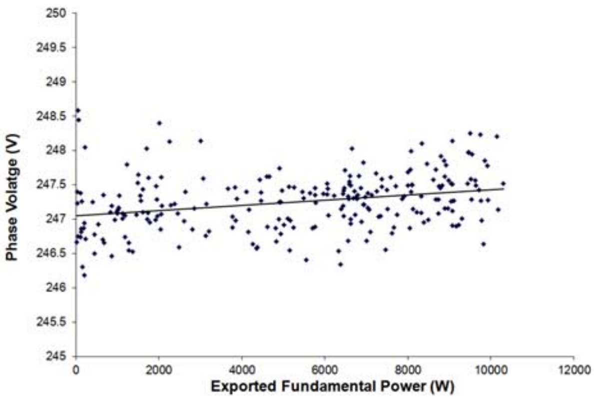

Fig.4, Increase of substation voltage with exported power. (18/05/11)

Fig.4 shows data in cases where the phase of the current indicates that the PV has a net export of power. A trend line is added to the data and this shows an upward slope of approximately 0.5 V increase in substation volatge over the generation range. The presence of network tap changes, as previously discussed, limit the utility of this type of plot.

Flicker

Flicker Pst and Plt was measured and logged at the north substation transformer. The prevailing level of Pst was less than 0.1 units and the presence of PV generation had a small and insignificant effect on Pst, increasing if prevailing level by about 0.05 units during periods of generation. The limit for Pst is unity.

Voltage Unbalance Factor

Voltage unbalance factor is defined in EN 50160 as the ratio of the negative sequence voltage to the positive sequence voltage. During period of no generation, at the north substation, phase L2 has a higher voltage than the other two phases by 1 to 2 V. The phase L2 also has the longest daily generation period of all the three phases, most likely due to the number and orientation of the PV panels. This combination leads to some voltage unbalance which worsens during generation. Highest unbalance of some 1 % is evident between 15h and 18h when, because of the PV installation configuration, phase L2 is generating and the other two phases are not. In all cases no unbalance factors above the 2 % limit in EN50160 were observed.

Distortion and Harmonics

It is instructive to examine the data for any effect of PV generation. Fig.5 shows a plot of total harmonic distortion (THD) for the three phases is plotted against power only for measurements where the PV is exporting.

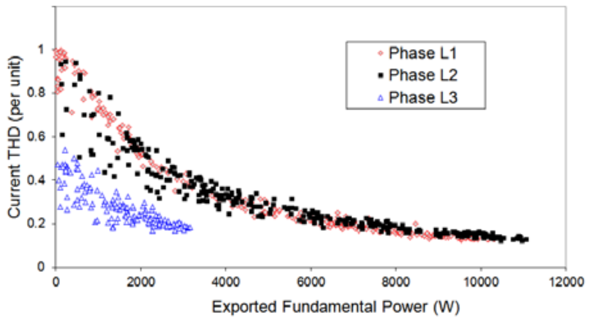

Fig 5, Current THD falling as exported power increases. (18/05/11).

It can be seen from Fig.5 that current THD (north sub.) falls as PV export increases. This effect occurs on all three phases, the L3 effect being less visible due to the lower generation on this phase (as discussed above).

The fall in current THD with generation is most likely to do with the increasing dominance of the sinewave (inverter output) generation current increasingly overwhelming generally low-level load current.

This is particularly true in the middle of the day when the domestic load is low and the generation is high. The load current is generally highly distorted as it associated with non-linear power supplies such as those in TVs and computers, whereas the PV inverter output current is assumed to be a low distortion sinewave.

This raises the issue (as with the case of reactive power) that whilst the fundamental current is supplied by the PV systems during periods of generation, the harmonic currents required by the agitate load, must be supplied by the network. This could lead to planning issues as the proportion of inverter-based generators continues to grow.

A similar plot to Fig.5 of voltage THD was made but is not shown. In this case the voltage THD at the substation transformer is broadly flat showing no obvious correlation with PV generation. Any effect of the lowering current THD on this feeder is insufficient to affect the low impedance of this network.

CONCLUSION

The monitoring of power quality on a low voltage radial feeder connecting a significant amount of PV generation reveals no critical power quality degradation during periods of PV generation.

The most significant effect seen during the study was a rise in voltage associated with PV generation. The analysis of the results presented shows that the voltage at the substation transformer increased by about 1 V during periods of generation. The rise in the middle of the feeder was more significant, showing a voltage change of about 4 V during PV generation. Voltage level analysis was hindered by voltage regulation tap changes in the network.

It is observed that the voltage on this network is at the high end of the statutory limits, which is typical of the UKs traditional 240 V infrastructure. Such mid-feeder voltage rise maybe of some concern to the networks operators when planning to add substantial PV to LV systems.

It is noteworthy that on average the PV units are generating at approximately half capacity on the sunniest days during the survey, which was conducted in the summer months. It is interesting to speculate as to effect of this finding on cost-benefit and CO_2 savings estimates that maybe used in such projects to justify investment.

The other point of interest is more general and concerns the supply of reactive power and harmonics during periods of PV generation. As the inverters in the system generate fundamental active power, the grid is required to supply the harmonics and the reactive power as it would without the presence of the PV, but with reduced billable watts.

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ACKNOWLEDGEMENTS

This work was supported within the UK BIS National

Measurement System Policy Unit's Program for Physical Metrology and partially funded by European Union's Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257.