WESTERN POWER DISTRIBUTION

INNOVATION

NEXT GENERATION NETWORKS

Solar Yield Network Constraints (SYNC)

Technique 1: Impact of cloud cover on PV dominated distribution networks

Study Results

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Glossary

Abbreviation	Term
CREST	Centre for Renewable Energy Systems Technology
DNO	Distribution Network Operator
DSR	Demand Side Response
SYNC	Solar Yield Network Constraint
ToU	Time of Use
WPD	Western Power Distribution

1 Project SYNC Overview

Western Power Distribution (WPD) has connected significant amounts of embedded generation to its distribution network in recent years. This includes a large variety of different technologies, dominated at first by wind and more recently by solar PV.

With so much generation already connected, and significant quantities in the pipeline, most of the latent capacity within the network has now been utilized. As such WPD is looking at ways of releasing extra capacity in the most economically efficient manner. Alongside the use of traditional reinforcement, the roll out of alternative connections has been one of innovative manners this has been done, building on the flexibility of generators. These give the option of trading off potential curtailment against capital expenditure and time delays.

Whilst we are now using the inherent flexibility of generation, at the moment the flexibility of the demand side is as yet untapped.

As part of the SYNC project we are looking to test a range of Demand Side Response (DSR) techniques with industrial and commercial customers to help address many of the different challenges being posed by PV generation.

There are 4 techniques that project SYNC will look to investigate:

(T1) - Automated demand increase / generation limiting in line with variation in solar yields.

(T2) - Directly matching flexible load with flexible generation

(T3) - Manually dispatched response signals from a WPD control facility (DSR)

(T4) - Creation of suitable ToU (Time of Use) tariffs to encourage appropriate demand

The project will require significant engagement and involvement of third parties including demand customers, generators, storage operators and National Grid. WPD will look to build on the learning gained in the FALCON project to maximize value to the industry and minimize the cost to customers.

2 T1 Overview

Alongside the steady state impacts of connecting PV on the network, there is a potential for high concentrations of PV generation to cause more dynamic issues. With generators drawing power from the same source there is the option for multiple generators to act in concert with changes in cloud cover. This could cause issues with voltage stability potentially increasing the use and wear on tap changers. Whilst this has been highlighted anecdotally, WPD has had no evidence of such issues occurring on its network.

T1 has concentrated initially on investigating the existence of, and implications of, these rapid variations. Should any issues be highlighted mitigation works will then be investigated.

3 Technique 1 Method

The initial investigations focussed on the existence of any rapid changes on the network and any potential implications.

This was split into two sections:

Literature Review – The aim of the literature review was to find and review reported evidence of, and solutions to, network operational problems caused by rapid variations of PV output. The scope for this included the following potential problems:

- - network voltage variations,
- - increased tap changer operations,
- - issues with voltage-control schemes,
- - power-quality issues, and
- - nuisance tripping.

Investigation of Existing Data – The research aimed to identify and investigate any adverse effects that solar PV generation may already be having on WPD networks, particularly on transformer tap changers. Existing datasets were used to provide an initial assessment whilst avoiding the cost of further monitoring.

The data included:

- Measured transformer current, voltage and tap changer operations from 96 substations in the midlands
- Measured solar irradiance from Met-Office weather stations

The aim was to identify and investigate correlations between the above data sets. The following datasets were also used:

- High-resolution irradiance data from CREST's own monitoring system
- Substation geographic and network map data from WPD
- Solar farm geographic locations from DECC

The investigations were carried out by CREST (Centre for Renewable Energy Systems Technology) at Loughborough University, utilising their significant expertise in the areas of both PV monitoring and data analysis. Their full report is available on request.

4 Literature Review

To review any existing evidence of PV causing rapid voltage fluctuations a literature review was carried out.

Extensive searching of available literature on an international basis yielded some, but not a lot of, concrete evidence. Much of the reported investigation is based on simulations with limited verification. Nonetheless, there are some useful insights worthy of note here.

4.1 Voltage Variations

Irradiance variations

Solar irradiance can vary rapidly due to passing clouds, and this variation is generally passed through solar PV systems (including their inverters) and will appear as power variations at the point of connection to the distribution network. As PV systems are not typically equipped with energy storage and therefore a reduction in irradiance can be expected to cause a reduction in power output, typically within one second. An increase in irradiance can of course be expected to cause an increase in power output, but this could be delayed by up to several seconds as the inverters adjust their operation point.

The impact of shading from cloud cover on the output of solar arrays can be non-linear due to the way some PV arrays are strung. As a result, the shading of just a small area of the array can cause a disproportionately large reduction in power.

However, this is mitigated on large arrays through their connections as multiple sub-arrays.

Distance Smoothing Effect

Several publications had used 1 sec data for their research. This is collected from a 20 hectare, solar site with 17 sensors (equivalent to 9MW). As seen in Figure 1, outputs from individual sensors show very high ramp rates. However, the average irradiance for all 11 sensors within the 20 ha rectangle has a much lower ramp rate. The plot also shows the corresponding irradiance curves for both of these cases plotted with a 1 minute moving average. This gives a much smoother profile and demonstrates the value of using high resolution measurements.

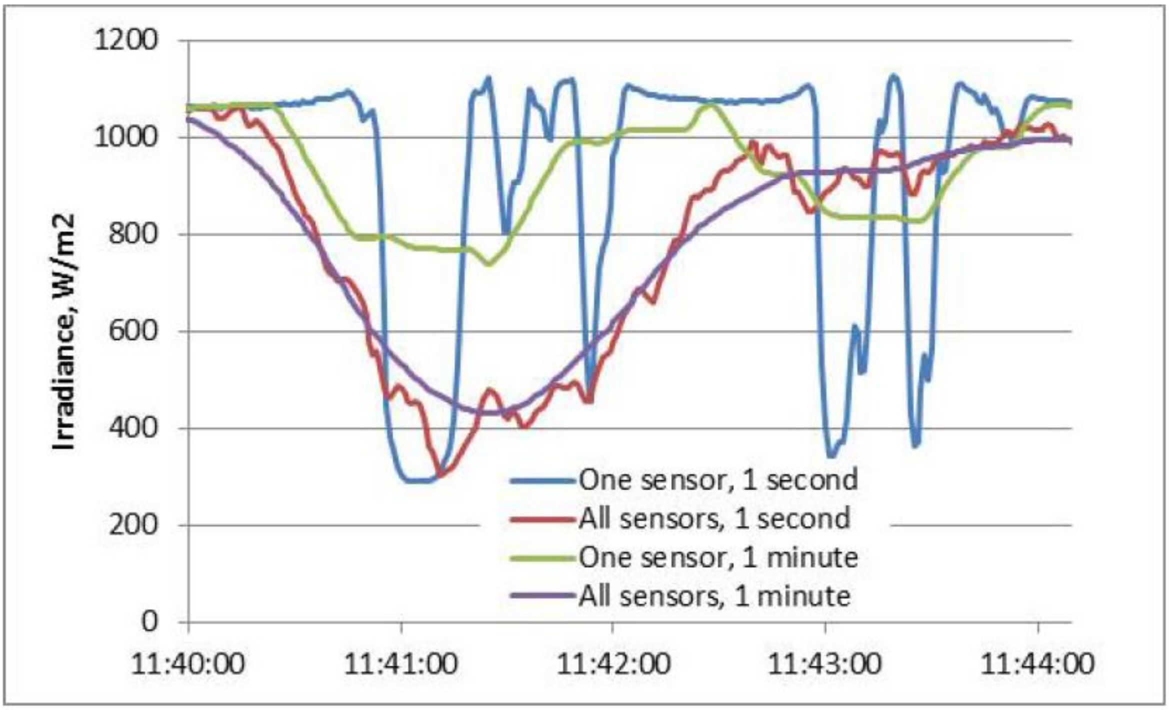


Figure 1: Sample irradiance data

When this same principal is then applied more widely to capture multiple solar farms the short term irradiance variations can be considered to be uncorrelated when they are widely spaced.

Cloud Edge Enhancement

An unexpected phenomenon in the data shows increases in the irradiance before and after the irradiance reduces. This effect has been characterised as cloud edge enhancement. This gives a short increase in the irradiance above the level expected for a clear sky index of unity. The enhancement effect occurs on both the ramp-up and the ramp-down of irradiance and can amplify the variations.

Tap Changing

High frequency tap operations were noted in a trial of regulated distribution transformers in Bavaria. The authors noted that the tap change operations were correlated with the solar irradiance profile. However, although the tap changes were clearly responding to changes in irradiance, the total number of 96 tap changes over a two-month period does not appear to be excessive or problematic.

Similar results were also encountered in research from higher voltage transformers. Increases in tap changes were recorded but not to the extent that they could be described as a problem or likely to result in increased operating costs of the distribution network for a typical transformer.

In the event that a transformer had little or no load and high levels of solar generation there is increased potential that it would experience a greater magnitude of changes in order to maintain voltage within the desired voltage band.

Tap Change Modifications

Several papers describe methods to reduce the impact of short term irradiance variations on the frequency of tap changes in regulated distribution substations for feeders with solar PV farms connected. We will not go into this in detail in this paper but full details are available in the original CREST report which is available on request.

Conclusion

Many reviewed studies report higher frequencies of tap changes as a result of high PV penetration. However, the increases are minimal when considered over the long life period of a tap changer life.

Other reports detail more onerous issues. However, these are mostly simulation-based and don't generally account for the averaging effect of spatial separation. This is especially relevant when using highly granular data.

4.2 Power Quality

Harmonics

In addition to the voltage concerns, some papers noted issues with higher order harmonics over 9 kHz. An example taken from German Distribution Networks is cited where customer equipment functioned incorrectly when nearby PV inverters were connected. The cause of this was attributed to high frequency distortion at 16 kHz and 18 kHz injected by the PV inverters.

A separate issue was noted in the same paper with low frequency oscillations at 9 Hz on a 400 V feeder. These were investigated when it was found that PV generation at some sites was interrupted when the inverters disconnected. Investigations showed that when power was exported from one of the PV sites, levels of the 9 Hz oscillation increased.

However, these issues were relatively rare and addressed by relatively simple and inexpensive reconfiguration of the physical connection arrangements.

Voltage Flicker

A study was found that used worst-case irradiance profile for a day with significant cloud variation. The simulation model then calculated the expected voltage flicker and compared it to the permitted maximum. This indicated that thermal and voltage limits would be exceeded before flicker became an issue.

Conclusion

There are potential risks due to high frequency harmonics and oscillation effects at low frequencies. These effects have caused inverter disconnections and so constitute a significant power quality concern to the customers with distributed generation connections. This is an area we recognise would benefit from for further investigation as the impacts of harmonics at frequencies outside of the ranges controlled by existing standards are not well understood at present and so may present an increasing risk in the future.

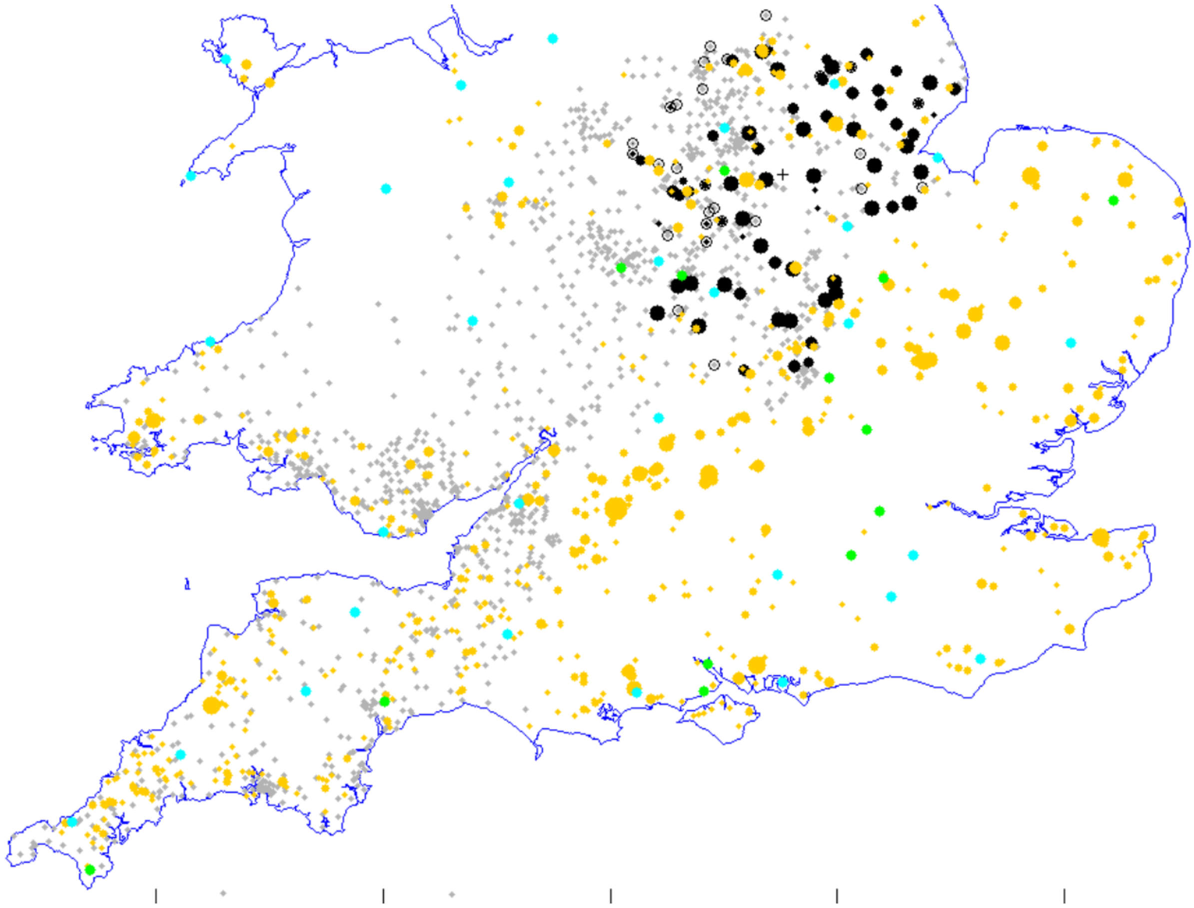
5 Data Analysis

Existing data sets were used to investigate adverse effects that solar PV generation may already be having on WPD networks, particularly on transformer tap changers. The data includes:

- Measured transformer current, voltage and tap changer operations from 96 WPD primary and BSP substations in the Midlands. This was at 1 minute resolution and included over 300 million data points made up of: transformer voltages, currents, tap positions, tap counters and several other measures
- Hourly measured solar irradiance from Met-Office weather stations, this includes solar irradiance data as well as cloud cover data
- High-resolution irradiance data from CREST's monitoring system
- Substation geographic and network map data from WPD
- Solar farm geographic locations from DECC

The analysis was completed using data for the whole of 2015.

The network data for the analysis was been gathered is shown in the map below.



KEY

Grey dots	WPD substations
Black dots	Substations with iHost – size of dot represents volume of date available
Black circles	iHost but no data
Yellow dots	Solar PV farms from DECC data base
Green dots	weather stations with irradiance
Cyan dots	weather stations with irradiance and cloud cover

Figure 2: Geographic representation of data available

The aim of the analysis was to investigate any correlations between the datasets to detect any causal links.

6 Results of Data Analysis

The graphs in Figure 3 highlight several key points from the analysis of the full data set. These present the 1 minute values of real and reactive current as well as power factor for Checkerhouse which has significant amounts of PV connected.

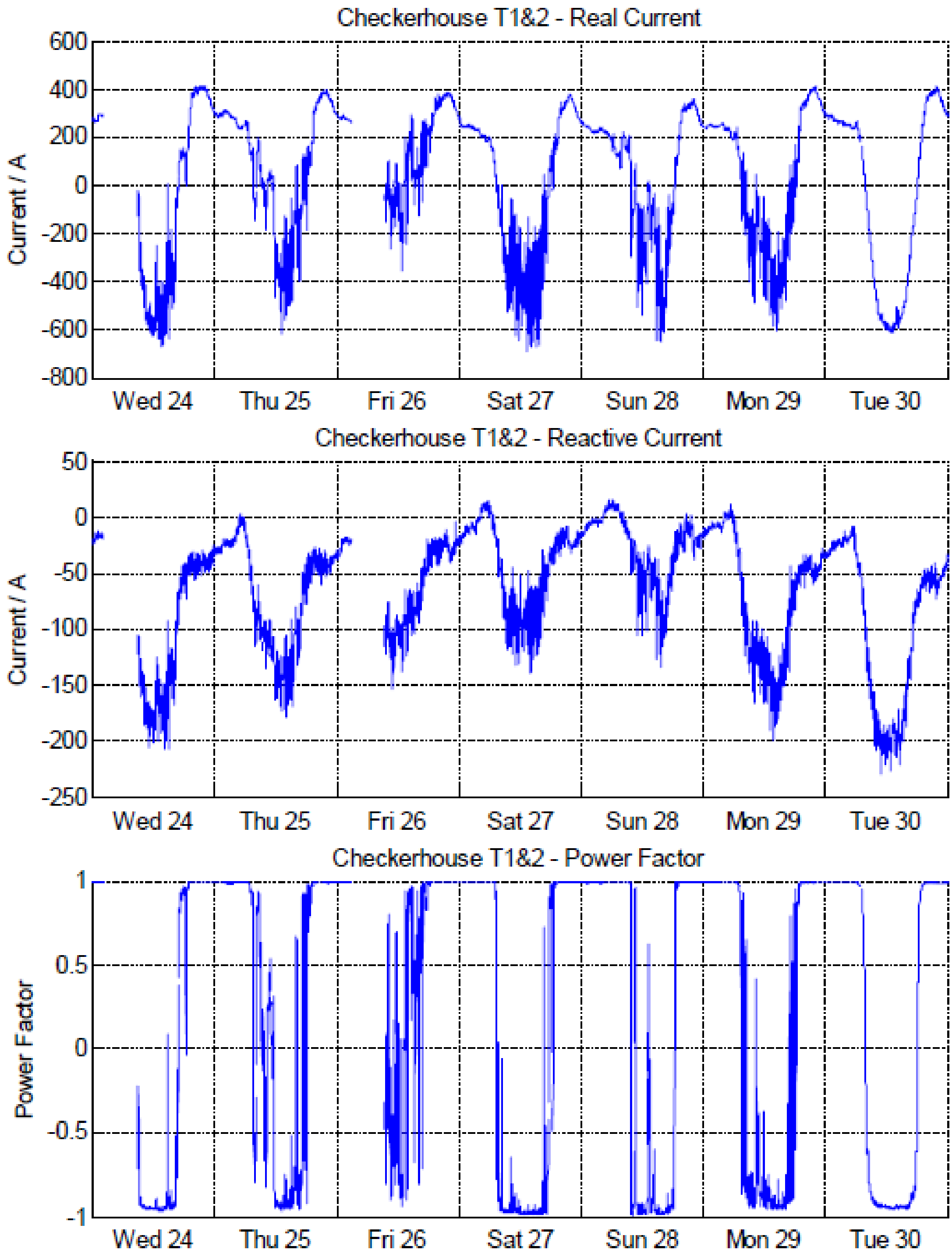


Figure 3: Checkerhouse real current, reactive current and power factor

There are several key observations:

- The presence of PV causes significant reduction and even reverse real current flow in transformers
- The level of reactive import into the system also increases with PV.
- There are significant rapid variations in real and reactive current due to PV. Swings of over 250A (15MW) in under 10 minutes are present.
- The power factor varies rapidly as the direction of flow changes.
- These changes aren't present for substations with little or no PV

Figure 4 shows the variability of the irradiance measured by CREST. This presents one day of high irradiance variability and another of low variability. The effects of this are clear to see in Figure 3. The rapid changes in irradiance are the cause of the changes in current

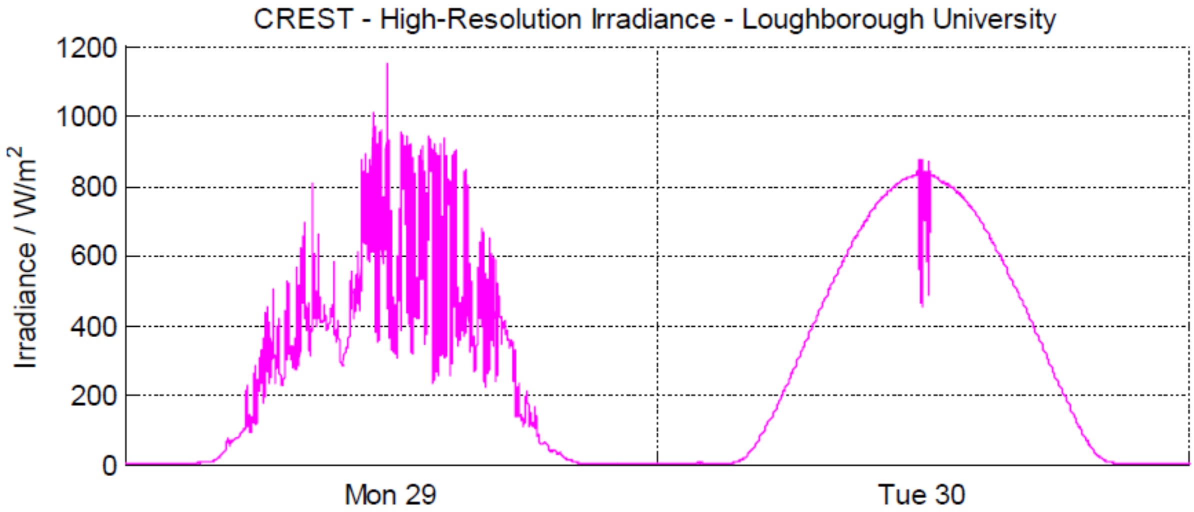


Figure 4: Irradiance data

In general the voltages measured are far more stable. For the measurement points:

- 99% of all measurements are within a 3% band
- 99.9% of all measurements are within a 4% band
- 99.99% of all measurements are within a 6% band

Figure 5 shows the yearly voltage of Gedling Primary substation which has significant amounts of PV connected. This shows the well-controlled voltage. This is very similar to a site with little PV.

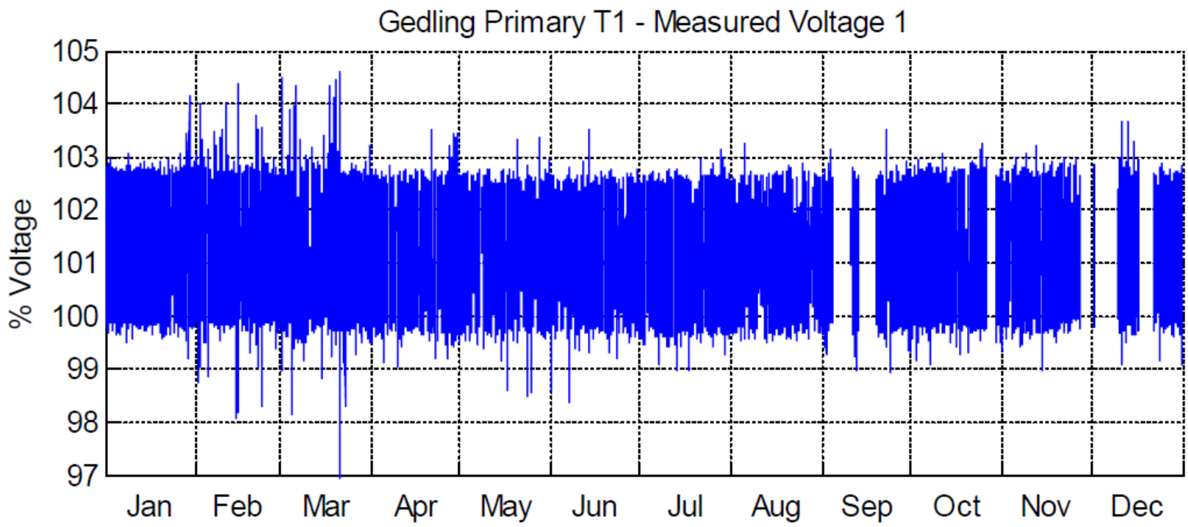


Figure 5: Gedling Primary year of measured voltage

Figure 6 and Figure 7 compare the 2 profiles in more detail and again show no clear distinctions. This is true for all the other substations analysed.

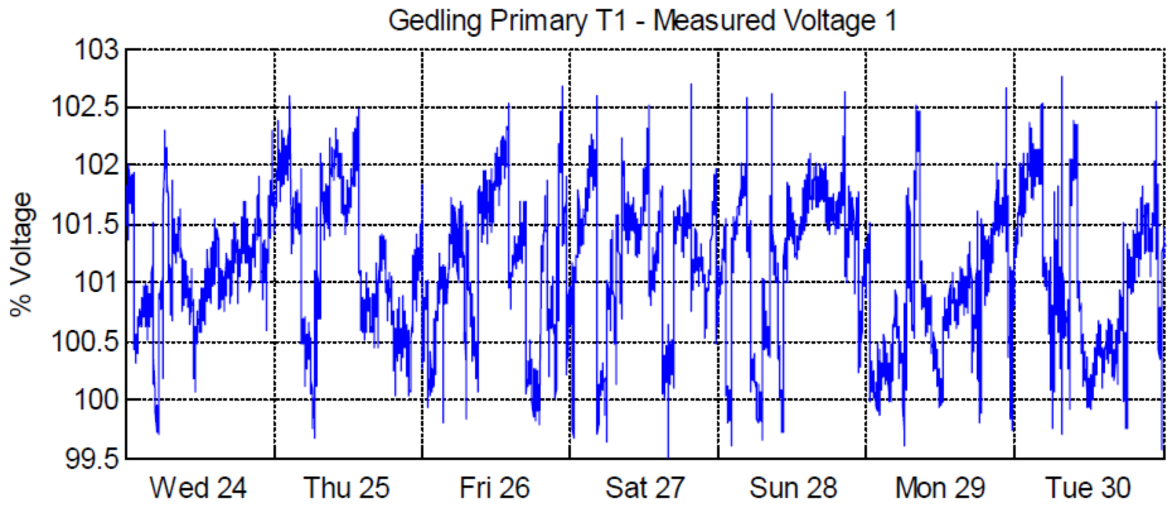


Figure 6: Gedling Primary week of measure voltage

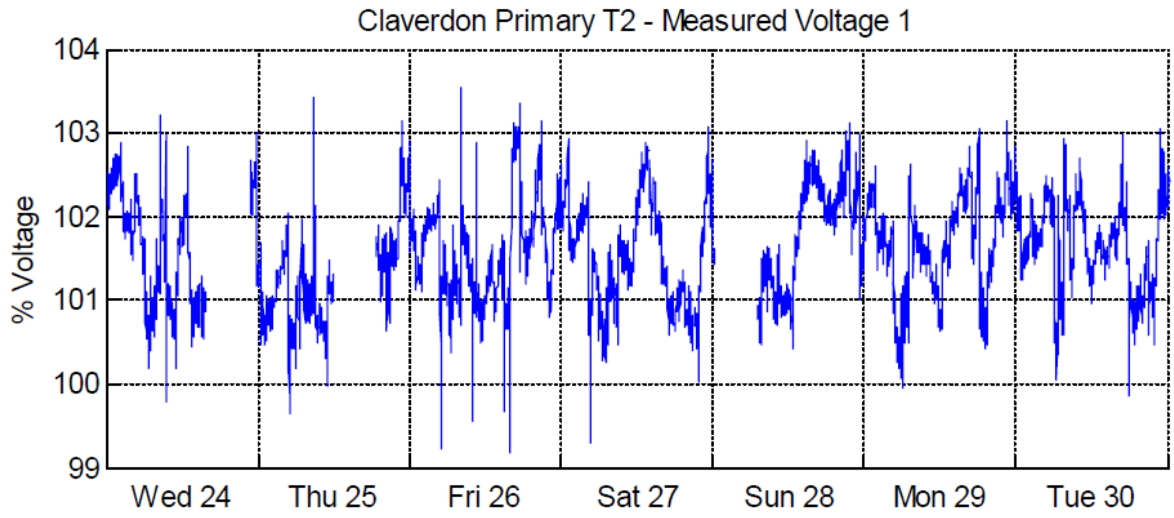


Figure 7: Claverdon Primary week of measured voltage

A well-controlled voltage is to expected and could be down to more active tap-changing. As such the number and frequency of tap change operations was investigated. Figure 8 and Figure 9 highlight the voltage and tap change operations at Northampton Grid on the 29th June (shown previously to have high irradiance variability). It shows just 7 tap operations in the day which provides a relatively stable voltage.

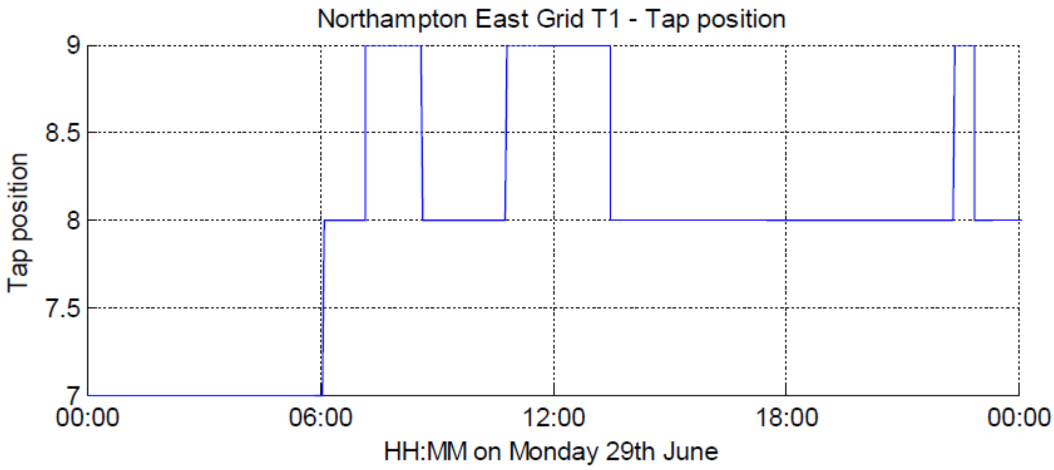


Figure 8: Northampton Grid Tap position

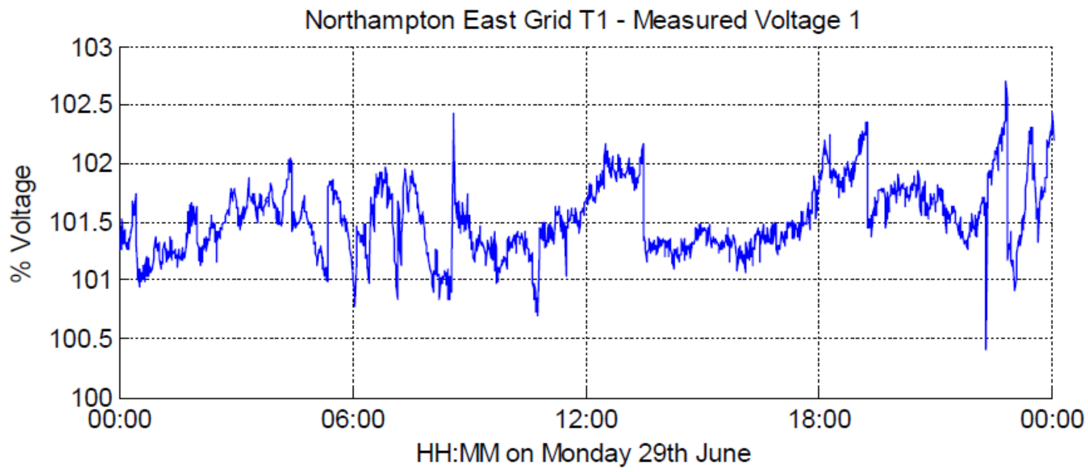


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Figure 9: Northampton East measured voltage

The distribution of tap changes throughout the year is shown in Figure 10. this shows that despite the high penetration of PV, the number of tap change operations decreases over the summer months.

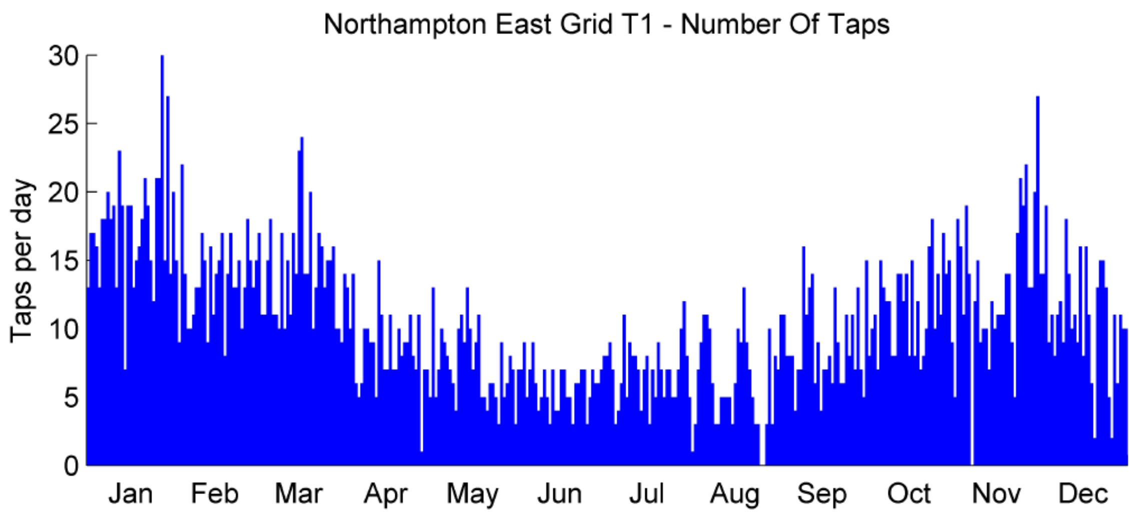

Figure 10: Northampton Grid yearly tap changes

7 Conclusions

The initial investigation into rapid fluctuations in voltage due to PV has uncovered no major issues. Whilst it is certainly true that cloud cover does create large changes in real and reactive current, the voltages observed remain within limits for the substations monitored. In general the literature agrees with this observation. There are no examples of major issues, with most concerns raised from very conservative modelling.

If you wish to receive a copy of CREST's full report or you have any additional research data that either supports or challenges the finding then please contact mwatson@westernpower.co.uk to discuss further.