THE DESERT KNOWLEDGE AUSTRALIA SOLAR CENTRE: HIGH VOLTAGE EFFECTS ON INVERTER PERFORMANCE.

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The significant increase in the penetration of PV into local electricity grids can lead to an elevation of AC grid voltage. This effect is particularly evident in mini grids operating in hot climates with long spur lines which, due to network requirements, already operate at relatively high AC grid voltages. The Desert Knowledge Australia Solar Centre (DKASC) was developed as a site where competing photovoltaic technologies could be installed, operated and monitored under the same conditions. Data from the DKASC has provided the basis for studying the impact of high grid voltage on the performance of inverters across the site. Assessment of the site data identified one system whose underperformance could be directly related to high AC grid voltage which was in turn linked to high local PV penetration. By reducing AC voltage to this array this issue was effectively resolved. The problems experienced by this one system at the DKASC was found to be the result of a combination of high AC grid voltage and low DC array voltage; which saw the inverter MPPT being forced to move beyond its effective working parameters and lead to a marked reduction in system performance. It can be demonstrated that high AC grid voltages can have a detrimental impact on the performance of PV systems. In locations with a combination of high AC grid voltage and high PV penetration this risk is accentuated and particular attention must be paid to ensure that the DC array voltage is significantly above the minimum recommended MPPT DC operating voltage.

Keywords: PV, Inverter Performance, High AC Grid Voltage, DKA Solar Centre,

1 PHOTOVOLTAIC SYSTEMS AND THE GRID

The increase in the size and the uptake of PV systems is leading to significant increase in the penetration of PV into local electricity grids. The increased penetration of PV is impacting on grid operation and in particular the voltage within the local grid can be significantly influenced by the various PV systems [1] [2].

Most electricity grids are typically designed to accommodate cascading voltage drop from the generating point through the network to the consumer. Significant PV input at the end of the grid can rapidly lift AC line voltages beyond the normal operating parameters. This effect is particularly evident in mini grids operating in hot climates with long spur lines, where the generating utility will often greatly elevate the generating voltage to ensure the voltage at the end of the furthest line is still within the desired operating range.

High grid voltages have the potential to effect the operation of PV inverters and in particular the operation of their inbuilt maximum power point trackers (MPPT's). Typical MPPT algorithms used within inverters will utilize the grid voltage as a reference point, and high grid voltages may cause the MPPT algorithm to operate in a non-optimal fashion. This may result in the need for alternative approaches to MPPT algorithms or settings for smaller grids or grids with very high PV Penetrations

2 DKASC SYSTEM DATA AND THE IMPACT OF PV ON LOCAL GRID VOLTAGE

2.1 Overview of DKA Solar Centre

The Desert Knowledge Australia Solar Centre (DKASC) was developed as a site where competing solar technologies could be installed, operated and monitored under the same conditions by an independent organization (Desert Knowledge Australia). All system data is freely available over the internet in real time from anywhere in the world. Over 30 solar technologies are now installed at this site with the majority of installations being multi string arrays of 5-6kWp and the total site output approaching 200kWp.

2.2 Overview of data monitoring

Every installation is connected to Class 0.5 AC power meters (IEC 60044-1) measuring a range of variables including AC Power, Voltage and Harmonics as well as DC variables measure within the inverter. All variables are sampled every second and 5 minute averages obtained. Additionally, a Class 1 weather station is also housed on site and all samples are synchronized to the PV system data.

The data gathered since the inception of the DKASC has allowed for the observation of the impact of high grid voltage on the performance of inverters across the DKASC site. The particular parameters that have been observed for assessment of this issue are

- AC grid voltage as seen by each inverter
- AC power out from each inverter
- DC voltage of each array
- DC current for each array
- Relevant meteorological data such as ambient temperature and global horizontal insolation

2.3 Impact of PV on local grid voltage

The DKASC is connected to and feeds into the local Alice Springs town electricity grid. Because of the towns remote location this local network is effectively an island grid that services a typical maximum demand of 55MW. The DKASC itself is located along the middle of a long spur line of this network, that services large loads at its distal end and typically sees an average grid voltage of 250-255V_{AC}. The nominal single phase voltage for end point users as specified by regulatory bodies for Australia is 230 V_{AC}.

As the DKASC has grown in size and overall PV output there has been over the same period a corresponding increase in the local grid voltage as seen by the inverters of the PV systems at this site. All indication are that this is a local effect and not related to any general network change or climatic conditions and the impact is consistent over both daily and yearly cycles. The long term upward trend in the local AC grid voltage as the more PV installations have been added to the DKASC site is illustrated in Figure 1.

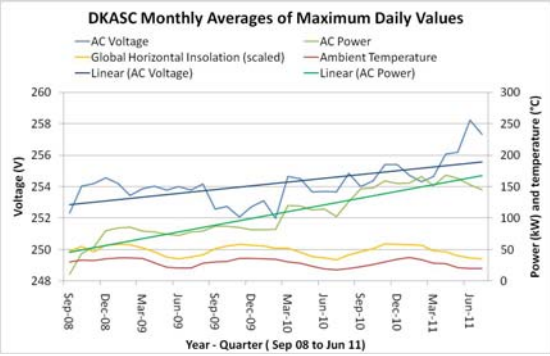

Figure 1: DKASC Grid Voltage and PV Output

3 DATA ANALYSIS AND ASSESSMENT

3.1 Approach to assessment

The rising AC grid voltage at the DKASC provided the opportunity to assess the operation of the many installed systems at the DKASC and determine if there was any associated impact on their performance.

The initial assessment covered all technologies at the DKASC site with the focus soon narrowing down to any technologies that were found to be underperforming. Underperforming systems were assessed to determine possible causes and determine any links to the issue of the high grid voltage.

The system data for the underperforming systems was also compared against control systems that were performing well but whose operating conditions had similar aspects to those of the underperforming system. As all systems were subject to the same high AC grid voltage, solar insolation level and ambient temperature, particular focus was placed on array specific parameters such as DC array voltage and inverter topology (transformer vs transformerless).

After this initial assessment was completed, and problematic PV systems identified, rectification works for these systems was undertaken and a further data assessment to determine the impact of these rectification works then followed.

3.2 Initial assessment

Of all the PV systems at the DKASC only one was found to be experiencing a significant underperformance. This was a recently installed dual axis tracking array which utilized a transformerless inverter. This underperformance was particularly notable because the same technology has also recently been deployed in other locations near to the DKASC where its operation had been noted for performing beyond expectations.

Figure 2 shows the key operational and output parameters for the underperforming tracking array for a typical clear day at the beginning of summer.

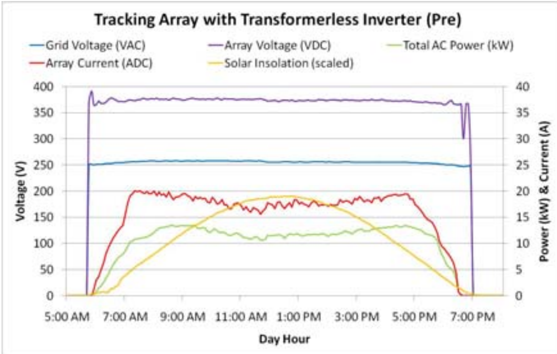

Figure 2: Underperforming Tracking PV Array

Figure 3 & 4 shows the same parameters for two other systems at the DKASC for the same day. One of these systems is a fixed array that like the tracking array utilizes a transformerless inverter however it differs from the tracking array in that its nominal DC operating voltage is significantly higher (Figure 3).

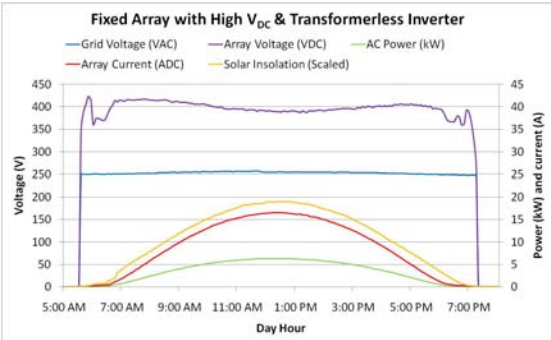

Figure 3: Fixed PV array with high DC voltage and transformerless inverter

Figure 4 shows another fixed array that like the tracking array has a low nominal DC operating voltage but differs from the tracking array in that it utilizes a transformer based inverter. Both of these two fixed arrays are operating correctly and are not experiencing and performance related problems despite the fact that they are also subject to the same high AC grid voltage. In this way they offer a very useful comparison with the tracking array that is experiencing problems.

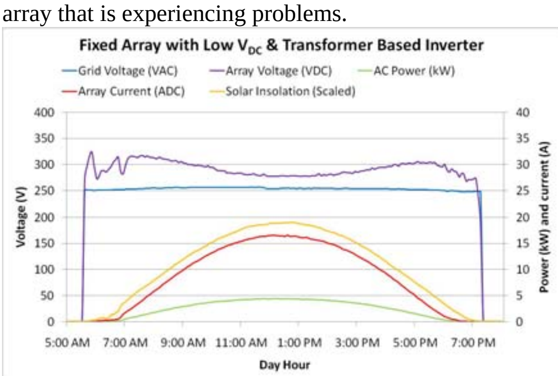

Figure 4: Fixed PV Array – with low DC voltage & transformer based inverter

3.3 Impacts identified in initial assessment

Examining the Figure 2 in detail shows the following four key phases of operation across the day can be seen for this underperforming tracking array

- Phase 1 - Time: ~ 6:00 -7:30

- Day starts, solar insolation rising
- Array voltage ~ $370V_{DC}$ & rising
- Grid voltage ~ $250V_{AC}$ & rising
- Array current rising
- AC power output rising

Even at this early stage it is evident that the starting point for the grid voltage is a relatively high $250V_{AC}$ and rising as the result of the whole of the DKASC slowly coming on line as the solar insolation increases. It can also be seen that for this tracking array is operating at ~ 370 V_{DC}, which is relatively close to the inverters minimum MPPT voltage but still within the recommended value.

- Phase 2 - Time: ~ 7:30 – 9:00.
  - Solar insolation continues rising
  - Array voltage ~ $375V_{DC}$ & stabilizing
  - Grid voltage ~ $256V_{AC}$ & rising
  - Array current peaks then begins a fluctuating fall
  - AC power output peaks then begins a fluctuating fall

As the morning progresses and the 200kW of PV systems across the DKASC start to deliver more energy onto the local grid the AC grid voltage also continues to rise. The DC array voltage however begins to plateau and the DC array current actually begins to falter and as a result power output also begins to falter.

It is useful at this point to examine the performance of the two fixed arrays at the same time (Figures 3 & 4) and to note whilst the tracking array is faltering these fixed arrays are increasing their power output. The essential operational parameter that separates them from the tracking array is that the DC voltage of these arrays starts to fall, whereas the DC voltage of the tracking array does not.

This is the essence of the problem experienced by the tracking array and focuses on the ability (or otherwise) of the array inverter to track the maximum power point of the array. Each inverter MPPT constantly works to balance the DC array voltage and current such that the resulting power output is maximized. The two fixed arrays have no problem doing this and as the data shows they easily reduce their DC array voltage as the array current rises. The tracking array however is unable to do this and its DC array voltage is kept much higher than is optimal and the result is a fall in array current (despite rising insolation levels).

- Phase 3 - Time: ~ 9:00 – 12:00.
  - Solar insolation continues rising
  - Array voltage: Stable ~ $375V_{DC}$
  - Grid voltage: Peaks/stabilizes at ~ $258V_{AC}$
  - Array current: Continues fluctuating fall
  - AC power: Continues fluctuating fall

As the day continues the AC voltage continues to rise as the combined system output across the DKASC also reaches its maximum and the voltage eventually peaks at $258V_{AC}$. This is also corresponds to the low point in the faltering output of the tracking PV array and the peak of the output from the fixed arrays.

- Phase 4 - Time: ~ 12:00 – 17:00.
  - Solar insolation peaks then falls
  - Array voltage: Falls slowly to ~ $370V_{DC}$
  - Grid voltage: Falls slowly to ~ $255V_{AC}$
  - Array current: Fluctuating rise
  - AC power: Fluctuating rise

From midday a slow recovery in the performance of the tracking array begins. This recovery corresponds to the combination of related factors that include a reduction in AC grid voltage and DC array voltage and a gradual fall in solar insolation. The fall in insolation leads to a slow fall in overall PV output at the DKASC site. This reduces AC grid voltage and corresponds to fall in the DC array voltage. Though not shown the ambient air temperature at the site at this time of day and this time of year would be approaching 40^{o} Celsius which would also contribute to the downward move on both AC and DC voltage at the site

3.4 Identification of central cause

As noted earlier the core of the problem with the tracking array is that inverter MPPT is unable to effectively track the maximum power output of this array because the DC array voltage is being constrained by external factors and is not able to fall in response to the needs of the MPPT. Figure 5 shows a typical IV curve for a solar cell and the relationship of array voltage, current and power. This figure shows that if the cell voltage is constrained at an undesirably high value the MPPT is unable to optimize the balance between voltage and current and power output will suffer.

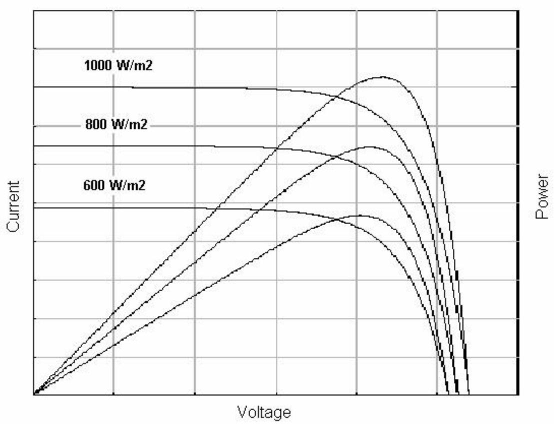

Figure 5: Typical IV curve

The cause of this can be attributed to a combination of three key factors

1. High AC grid voltage
2. Low DC array voltage configuration
3. Inverter MPPT constraints

The first of these, the high AC grid voltage is a known issue at the site, but as the assessment shows the vast majority of the systems at the DKASC are not adversely affected by this. Similarly with the low DC array voltage, it is evident that it does potentially reduce the scope of the inverter MPPT to maneuver itself into an optimum balance between voltage and current, but as the array shown in Figure 4 demonstrates this is not always the case. Therefore for this issue to develop the additional factor that is required to be present is that the array inverter MPPT itself must have operational or parameter constraints in place that in combination of high AC grid voltage and low DC array voltage lead to non optimal performance.

The inverter used by the tracking array has a non-programmable setting known as the *minimum MPP voltage*. This parameter increases in a linear fashion with as the AC grid voltage increases. The AC voltage at the DKASC reached ~ $358V_{AC}$. The corresponding *minimum MPP voltage* for this AC value is ~ $372V_{DC}$ which is very close to the actual operating DC array voltage for this system at the time it was faltering. Information from the inverter manufacturer emphasized that at the *minimum*

MPP voltage the inverter will still operate but the ability of the MPPT to effectively track the maximum power point of the array is severely compromised. This is the problem that was experienced by the tracking array and the central reason that power output fell away as the AC grid voltage increased. The other arrays at the site whose DC array voltage was also low did not experience these issues because the inverters they used had a much lower *minimum MPP voltage* parameter (i.e. ~ 275V_{DC} at a AC grid voltage of 358V_{AC}.).

It should also be noted that the inverter topology itself (transformer vs. transformerless) does not seem to be significant causative factor in this issue, and any impacts it does have would likely be only secondary effects on the inverter manufacturers determining of such parameters as the *minimum MPP voltage.*

3.4 Rectification and reassessment

Once the issue was clearly identified the two best means of rectifying the problem were determined to be either an elevation in DC array voltage or the reduction in the AC grid voltage. As a first step the former of these options was adopted and the tracking array strings were reconfigured to increase the DC array voltage, so that it was unlikely to approach the *minimum MPP voltage* parameter. This resulted was an immediate recovery in the power output of the system. However this reconfiguration was a temporary measure only, as it was not possible with this new configuration to utilize all of the PV modules installed on the tracking array and there was no wish to leave modules idle. The exercise did however further confirm that high and AC grid voltage and the relatively low DC array voltage in combination were the root cause of the problem

The long term rectification solution for this particular array was to decrease the AC grid reference voltage. To this end an autotransformer was installed on the AC line to this particular system, which effectively reduced the AC grid reference voltages for this tracking systems down from 255-260V_{AC} to a more operable ~245V_{AC}. The result of these rectification works was the return of the tracking array to a higher level of performance. This was confirmed through a reassessment of the system data after that was carried out after the rectification works were completed.

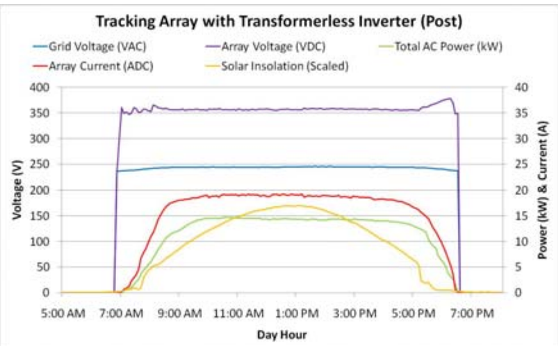

Figure 6: Tracking PV array post rectification works

As Figure 6 demonstrates, the reduction in AC grid voltage has in turn allowed the inverter MPPT to operate at a lower DC voltage and the reduction of this constraint has improved the overall output of the array significantly. At this new AC voltage of ~245V_{AC} the DC array voltage has been better able to respond to the requirements of the MPPT and the DC current has been able to rise and output of the system improve. However it should be noted that the DC voltage still remains close to the new *minimum MPP voltage* parameter (for the new AC voltage) and that the effects of operating at this margin are still evident to a minor degree.

This effect can be seen in the "flatness" of the array current and power curves during the peak solar hours of the day. Much of this effect is obviously attributable to the fact that this array is dual axis tracking. But despite this it seems apparent that the MPPT functionality of the inverter is still constrained by a small degree and a further reduction in AC voltage will allow additional improvement in array output.

As a means of comparison Figure 6 shows the relationship between DC and AC voltages for this tracking array both before and after the rectification works.

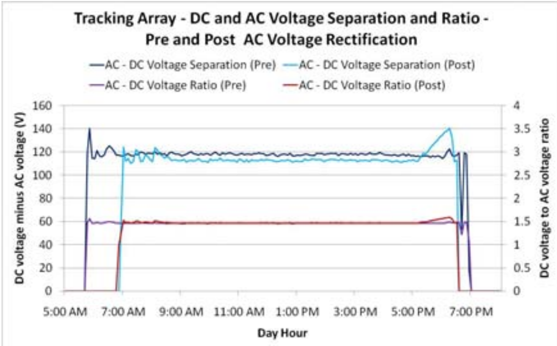

Figure 7: DC – AC voltage: pre and post rectification

The relationship between the AC voltage and the *minimum MPP voltage* parameter is known to be a linear ratio of approximately 1:145. Figure 7 shows the same relationship between the AC and DC voltage which suggests that despite the improvement after rectification, the high AC voltage still constrains the DC voltage from falling to its most optimal operating value and thus the overall system output is similarly constrained.

4 CONCLUSIONS

The performance related problems experienced by the tracking array at the DKASC were determined to be the result of the combination of three key factors

1. High AC grid voltage
2. Low DC array voltage configuration
3. Inverter MPPT constraints

The potential impacts of this combination of operating conditions on the output of a PV array are non trivial, with the demonstrated reduction of 20-25% of the overall output of the array in the cited example.

As a result of these finding it can be seen that high AC grid voltages are a less desirable outcome of high PV penetrations, particularly in smaller and more isolated grids. While it is generally assumed that as long as the AC grid voltage is within the operating parameters of the inverter being used for the grid connection of the PV system, the AC grid voltage does not influence the operating performance of the system.

It can now be demonstrated that in certain circumstances high AC grid voltages can have a detrimental impact on the performance of PV systems and that where high AC grid voltages are present particular attention must be paid to the DC array voltage configuration and its relationship to the inverter MPPT parameters.

5 REFERENCES

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[2] C Whitaker, J Newmiller, M Ropp, B Norris (2008). “Distributed Photovoltaic Systems Design and Technology Requirements,” Renewable Systems Interconnection Study. Sandia National Laboratories. February 2008. 8.