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# OPTIMISING PV ARRAY PERFORMANCE USING REAL TIME MEASUREMENTS

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## ABSTRACT

BP Solar is involved in long term studies on IV swept, Maximum power point tracked or grid connected arrays at currently 67 sites worldwide [1]

Recent studies [2][3][4][5] have shown that many PV arrays can suffer lower performance than expected due mainly to BOS limitations like Inverter efficiency, mismatch, shading, thermal losses and $V_{MAX}$ tracking accuracy. This paper discusses mathematical methods used to analyse instantaneous or averaged array data in real time to determine when arrays are not performing optimally and shows how to help identify what is causing the loss. Empirical equations are introduced to help determine what Power the system should be producing during each measurement period.

## 1. ARRAY MEASUREMENTS AND DEFINITIONS

Monitoring of arrays at different sites is usually performed between every 15secs - 30 minutes and some of the important parameters are shown in Table I.

**Table I.** Some of the important parameters measured and calculated. See also IEC 61724 [6]

| Abbreviation | Parameter Name | Unit | Range or Normalisation |
|---|---|---|---|
| $G_I$ | Irradiance | kW/m² | 0 to 1.4 |
| $T_{AM}$ | T Ambient | C | -40 to 100 |
| $T_M$ | T Module | C | -40 to 100 |
| WS | Wind Speed | $ms^{-1}$ | 0 to ? |
| YR | Insolation | kWh/m² | $= \Sigma G_I$ |
| $V_{DM}$ | DC Voltage | | $= V_{DC}/V_{MAX.STC}$ |
| $I_{DM}$ | DC Current | | $= I_{DC}/I_{MAX.STC}$ |
| $I_{DN}$ | Normalised DC current | | $= I_{DM}/G_I$ |
| YA | DC yield | Wh/Wp | $= P_{DC}/P_{MAX.STC}$ |
| YF | AC yield | Wh/Wp | $= P_{AC}/P_{MAX.STC}$ |
| $PR_{DC}$ | Performance Ratio DC | - | =YA/YR |
| $PR_{AC}$ | Performance Ratio AC | - | =YF/YR |
| LC | Capture Loss DC | - | =YR –YA |
| LS | System Loss AC | - | =YA –YF |

## 2. SWEPT IV vs. MPPT vs. INVERTER MEASUREMENTS.

2.1 DC IV SWEEP, SINGLE MODULE

Characterisation of PV Modules can best be done by performing regular IV sweeps while recording the Irradiance, Ambient and Module Temperatures and other Meteorological conditions during the sweep. Angle of incidence, temperature, diffuse/direct and spectral effects then contribute to the module's performance and there are no BOS errors or losses that need to be subtracted out.

Figure 1 shows IV traces for a c-Si Module in Australia, taken once every 30 minutes during a sunny morning (traces were very similar in the afternoon except the voltages were slightly lower as Temperatures tend to be higher for the same Irradiance).

"$G_I$" shows the Irradiance (right hand Y-axis) versus Time of day (X axis). "$V_{MAX}$" indicates the maximum power point voltage found by the IV sweep, this is what MPPTs should (but don't always) find for best performance.

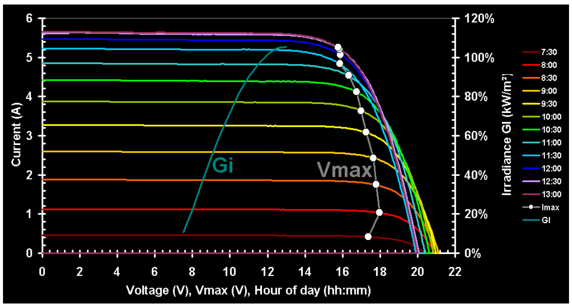


**Fig 1**. Swept IV traces every 30 minutes for a c-Si Module on a sunny morning in Australia showing the Irradiance versus time and the true $V_{MAX}$ for every measurement.

The swept IV data can be further analysed to derive $I_{SC}$, $R_{SHUNT}$, Fill Factor, $R_{SERIES}$ and $V_{OC}$. Note how the $R_{SERIES}$ ($-dV/dI|_{VOC}$) and the $V_{OC}$ are both lower at noon where the Irradiance and $T_{AMBIENT}$ are higher.

Figure 2 shows some of these data plotted against Irradiance $G_I$. Note the shapes of the $V_{DM}$ and $I_{DN}$ curves – this is the correct behaviour for a good module – both are linear at low light levels, $V_{DM}$ falls slightly and $I_{DN}$ can rise slightly at higher irradiances where temperatures are higher. The YA (dc Yield) curve also shows good low light level performance and rises slightly less than linearly at high light levels because of the $V_{MAX}$ drop. LC shows the DC Capture loss (YR – YA), which is very small at low light levels.

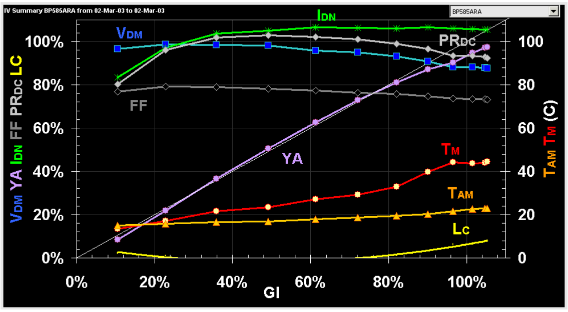


**Fig 2.** Derived Parameters from swept IV traces for a good c-Si module in Australia versus Irradiance.

These curves can characterise specific module types (technologies will differ slightly) and show what the module is capable of when being measured without external losses.

When measuring DC data with MPPTs or AC data with Inverters these can and do both introduce errors (e.g. imperfect Voltage tracking) and losses (e.g. BOS Parasitics and Inverter Inefficiencies) in the reported performance that are not necessarily due to the module technology itself.

2.2 DC MODULE MPPT, SINGLE MODULE

Maximum Power Point Trackers are used to try to bias the Modules at the Voltage at which the Power output is a maximum, however they have to cope with constantly changing temperatures and Irradiances and may introduce parasitic losses of their own.

Figure 3 shows a typical trace for a similar c-Si module on a sunny morning in Germany using a custom built MPPT. The Irradiance data was not quite as smooth as the Australian morning in Figure 2, the module temperature was slightly hotter and the latitude further from the equator so that the corresponding Air Mass was higher. The $V_{DM}$ trace seems to have overcompensated slightly which will result in reduced power. Now there is a finite capture loss LC at all light levels, indicating that just having an MPPT has added a loss mechanism not there in the IV swept trace in figure 2.

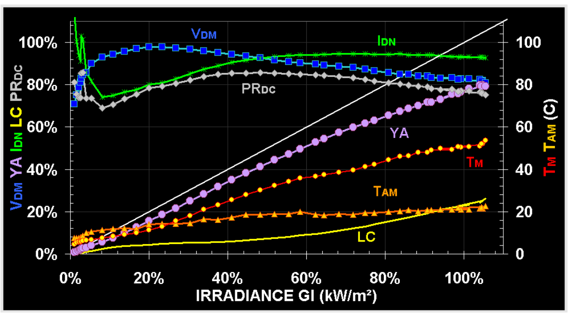


**Fig 3.** Derived Parameters from DC MPPT for a good c-Si module in Germany versus Irradiance.

2.3 AC WITH INVERTER, ARRAY OF MODULES

When measuring arrays of modules, losses such as mismatch, connections, wiring and shadowing can become significant. Also the AC output will depend on the Inverter efficiency (which may be stated in the data sheet) but cannot be assumed unless the dc parameters are measured simultaneously to prove it. Some Inverters infer their dc parameters from look up tables and large inaccuracies have been seen.

Figure 4 shows a 1.5kWp STC c-Si roof top array in California with a 4kWp Inverter (much larger than would normally be used). DC parameters are not available but the Final Yield, AC Performance ratio and total Loss (= $L_{CAPTURE}+L_{SYSTEM}$) are plotted.

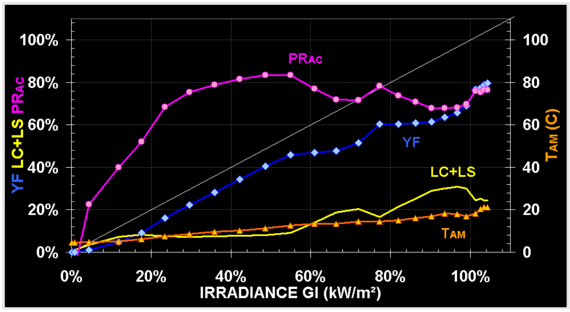


**Fig 4.** Rooftop 1.5kWp STC c-Si Array with 4kW Inverter on a Sunny morning in California versus Irradiance

For comparison Figure 5 shows the performance of a curved rooftop system with c-Si in the USA against Horizontal Irradiance.

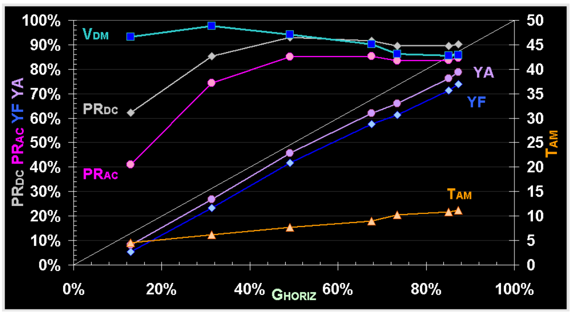


**Fig 5.** 60kWp STC c-Si curved rooftop, sunny morning, USA.

Both figs 4 and 5 are clear sunny days with no shading. However the YFs have differing losses at low light level and high light levels. The YF should normally be a smooth curve, but clear glitches can be seen in fig 4. This is probably due to the Inverter hunting for the correct $V_{MAX}$ and losing power when it is away from this value. The YF is further from the YR around noon because the rooftop array is quite close to the roof so there will be a thermal rise and also this is the ac Yield so that Inverter losses will lower the YF.

Even though fig 5 is a curved roof, it shows better performance at higher light levels (when clear skies will give mismatch between strings with differing tilts) indicating that the losses in Fig 4 are dominated by BOS system components as the modules are of the same type.

## 3. EMPIRICAL FORMULAE

To study the output performance of data Empirical formulae can be used. Equation (1) is used to predict Yield as a function of $G_I$ plane of array irradiance, $T_{AM}$ ambient temperature and WS wind speed. A best fit to logged data is obtained by minimising rms errors (2) varying the parameters: -

**A** (linear, dominant total system performance)
**B** (non linearity)
**C** (Temperature derating)
**D** (wind speed sensitivity)
**E** (a BOS related constant loss figure).

**Table II.** Empirical formulae

| | |
|---|---|
| $Y_{CALC} = \Sigma G_I*(A+B*\Sigma G_I+C*T_{AM}+D*WS)-E$ | (1) |
| $Y_{ERR} = [\Sigma(Y_{MEASURED}-Y_{CALC})^2]^{0.5}$ | (2) |
| $T_{MODULE} = C'*T_{AM} + \Sigma G_I*(A' + D'*WS) + E'$ | (3) |
| $V_{ARRAY} = A''*LOG_{10}(\Sigma G_I) + C''*T_M + D''*WS + E''$ | (4) |
| $A = A_{SYSTEM}*A_{INVEFF}*A_{P.ACTUAL/P.NOMINAL}* A_{STABIL'N}(\text{exposure})*A_{SPECTRUM}(\text{time of year})$ | (5) |

Other empirical equations for $T_{MODULE}$ (3), $V_{ARRAY}$ (4) and incorporating seasonal and stability effects into Yield (5) are shown in table II.

## 4. ANALYSING STABILITY AND CONTINUED GOOD PERFORMANCE

For stable performance the maximum value of PR (high Irradiance days) allowing for any seasonal effects should be fairly constant with time. An empirical fit using equation (1) done at the beginning of the measurements then extrapolated to subsequent data should still predict performance well if the array is stable and still working correctly. The predictions from equations (1), (3) and (4) can be used to validate the performance of the array using the real time monitoring. Figure 6 shows the 21$^{st}$ of each second month for a c-Si array in Tennessee. The measured final yield YF is near that calculated $YF_{CALC}$ when the array is working correctly.

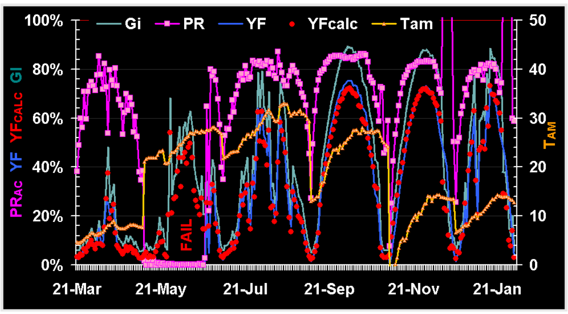


**Fig 6.** Good stability and performance from a c-Si Array in Tennessee except downtime 21$^{st}$ May.

## 5. STRINGS

Equal sized, planar strings should contribute equal fractions to the total power output at all times that there is no shading. With curved roofs allowances need to be made for incidence angles particularly in sunny conditions. Figure 7 shows the performance on a bright winter day (low sun) of an "as setup" 13-string a-Si array on a curved roof in an urban environment near Sydney, Australia. The six "East strings" face slightly east, those 6 "West strings" face slightly west and therefore contribute higher in the afternoon. The string marked "FAULT" had a fault as it was set up resulting in intermittent performance, The "Centre" string faced east at one extremity, was horizontal in its middle and west at the other end and by comparison had good performance all day. Real time monitoring was set up to study the difference in performance suggesting changes to be made to improve the performance of the poorer strings.

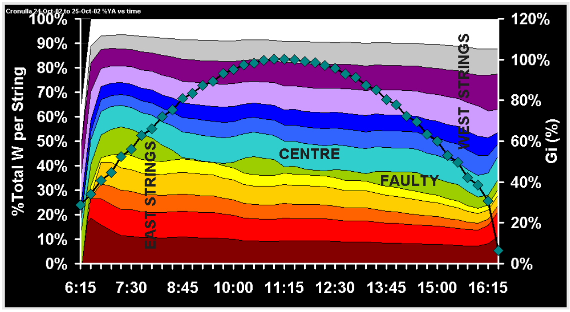


**Fig 7**. Variable Percentage of Total W from 13 strings and Horizontal Irradiance (as initially set up) on a curved roof, Winter in Australia

## 7. CONCLUSIONS

- Real Time monitoring has been set up and used on multi string arrays with partial shading and curved orientations to understand and improve performance.
- Many BOS and system limiting problems have been found that mean ac $kWh/kW_P$ measurements aren't always indicative of module technology.
- These quick diagnostics will result in better uptime, improved performance and a lower energy cost per kWh


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