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ADVANCED ANALYSIS OF PV SYSTEM PERFORMANCE USING NORMALISED MEASUREMENT DATA

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ABSTRACT

The performance of grid connected systems is usually reported by AC energy (kWh/kWp) and performance ratio (PR) values [1].

If there are any outages or underperformance due to temporary faults or effects like shading these all need to be carefully corrected to give a true value for the performance otherwise these systems specific losses can dominate comparative kWh/kWp values.

This paper proposes a way of calculating system performance using the final yield YF and the performance ratio versus plane of array irradiance G_I. When the system is performing well the data points will be in a narrow range that can be curve fitted with empirical formulae.

Underperforming points (which may depend on random events like outages) can be easily identified as they will not lie on this narrow line.

The expected yield in kWh/kWp can then be determined by folding in the curve fit to the good performance points by the expected irradiance and temperature data.

These techniques are being used to test different module technologies and improvements such as anti reflection coated glass in Sydney, Australia and at ISET in Kassel, Germany

INTRODUCTION

As system performance will be influenced by balance of systems effects the data below characterises individual dc modules measured in Sydney with an IV sweep to minimise any voltage mistracking losses.

Figure 1 shows the dc Yield YA and performance factor PF of a BP7180 module in midwinter when there was a known shading problem in the early morning and late afternoon (the inter-array spacing had been designed for ~85Wp modules each about 1.2m tall, but when larger ~170Wp modules 1.6m high were fitted the tops of front array shaded the bottoms of the modules on the back array - it took some time for the arrays to be moved further apart and the measurements were still progressing, so the effect of this shading needed to be analysed and corrected).

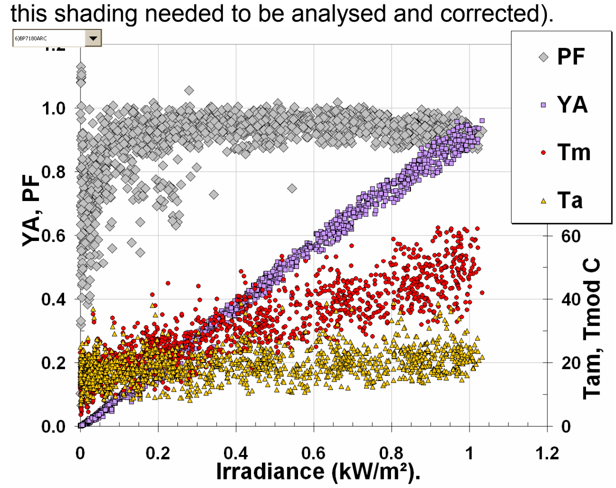

Figure 1 : DC yield (YA), performance factor (PF), T_{MODULE} (T_M) and $T_{AMBIENT}$ (T_A) versus plane of array irradiance (kW/m²) for a BP7180 module in Australia. Winter months, morning and evening shaded points included.

When underperformance occurs due to problems like voltage mistracking and shading, the performance points will occur on outliers below the main curve. The number of points displaced from the curve multiplied by their distance from it will give an indication of the energy loss of the system.

Figure 2 shows the same data but filtering out the time when the shading occurred. The spread in data points (particularly performance factor at low irradiance) are now much narrower and show the good low light level characteristics down to <100W/m² for the BP7180. The variability seen in PF is mostly due to the variation in T_{MODULE}, at 1kW/m² irradiance the T_{MODULE} can be between 40°C and 60°C leading to a 9% variation in Performance factor (as the gamma factor $1/P_{MAX} * dP_{MAX}/dT$ for a crystalline Si module is normally around -0.45%/deg C)

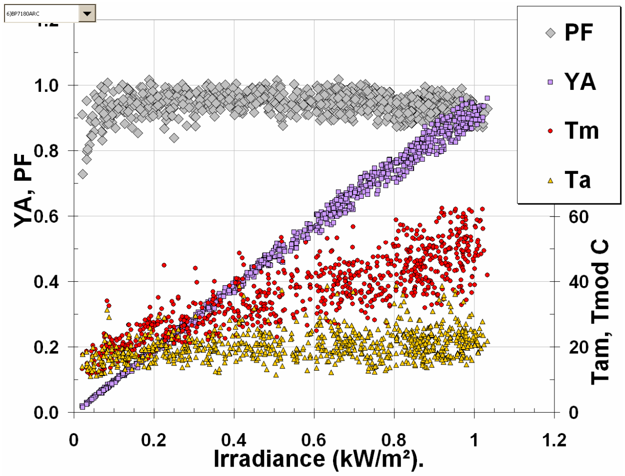

Figure 2 : Data from figure 1 when there was no shading. Note the much smoother performance factor at low irradiance when shaded points are eliminated.

Voltage mistracking can also be studied by plotting the normalised voltage $V_{DM} = V_{DC}/V_{MAX.STC}$ against time or Irradiance. (For most modules this value will be in the range 0.85 to 0.95, slightly dependent on module temperature).

Figure 3 shows the V_{DM} against Irradiance with generally good voltage tracking, most of the outliers from figure 2 (for example there are 4 points between 0.2 and 0.3 kW/m²) can now be seen to be due to the occasional low tracking voltage.

Also shown is the normalised DC current $I_{DM} = I_{DC} / I_{MAX.STC}$. When there is no shading and the V_{DM} is correct the I_{DM} should be nearly equal to the Irradiance.

It shows most of the I_{DM} values are on or near the line with a gradient of 1:1.

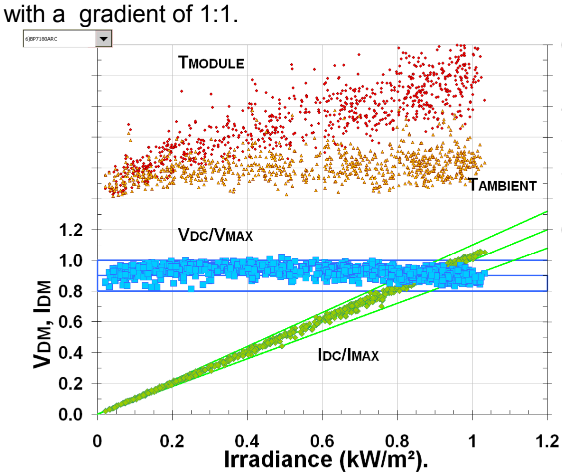

Figure 3 : Normalised DC voltage V_{DM} and DC current I_{DM} for non shaded hours for the BP7180 in Australia.

When there are no system limiting effects like shading and poor voltage tracking the module array performance can be modelled with empirical formulae (1) to (4) fitted to the measured data. Table II shows the formulae used to calculate dc Yield, T_M and V_{DM} as functions of irradiance, T_{AM} and wind speed.

Table II. Empirical formulae

$Y_{CALC} = \Sigma G_I*(A+B*\Sigma G_I+C*T_{AM}+D*WS)-E$	(1)
$A = A_{SYSTEM}*A_{INVEFF}*A_{P.ACTUAL/P.NOMINAL}*A_{STA-BIL'N}(\text{exposure})*A_{SPECTRUM}(\text{time of year})$	(2)
$T_M = C'*T_{AM} + G_I*(A' + D'*WS) + E'$	(3)
$V_{DM} = A''*LOG_{10}(G_I) + C''*T_M + D''*WS + E''$	(4)

Table III shows the coefficients fitted to this module. There is good correlation with RMS Errors of less than 3% for V_{DM}, 1.1% for YA and less than 2C for T_{MODULE}.

Table III. Empirical fit coefficients to table II equations

	V_{DM}	Y	T_M
A ~ Irr	0.104	1.09	39.5C
B ~ Irr²		-0.088	
C ~ Tam	-0.39%	-0.45%	1.12C
D ~WS	0.20%	1.1%	-4.2C
E ~ Const	1.10	0.011	-3.2C
RMS Err	2.8%	1.1%	2.0

Figure 4 shows how well the calculated V_{DM}, YA and T_M values correlate the measured when there is no shading and the measurements are good.

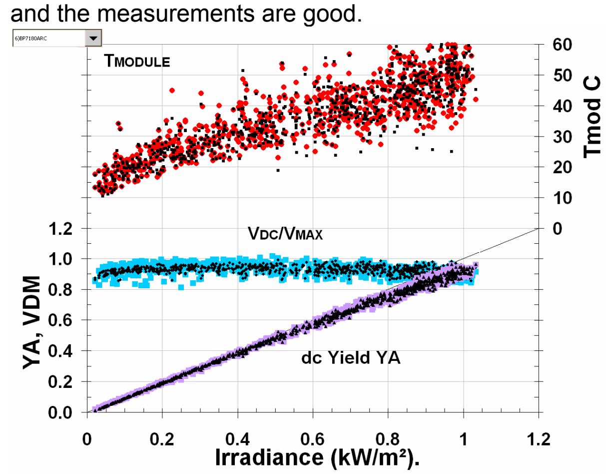

Figure 4 : Calculated (1) to (4) vs measured values of V_{DM}, YA and T_{MODULE} for a BP7180 in Australia.

The losses from the measured versus the expected yield can be quantified by summing the difference in yield for each outlier data point below the empirical curve fit.

ANALYSING REAL AC ARRAY DATA

These techniques were then used to study the differences between predicted and measured yields for some large arrays.

Table IV shows details for two of the AC systems studied and some of their known yield affecting parameters. (System A was reported at the 19th PVSEC, Paris 2004 [3]).

Table IV : Details of two large AC grid connected arrays studied

System	A [3]	B
Type	Retrofit roofs	New Roofs
Location	Australia	UK
YR Insolation kWh/m²/y	~1700	~1100
Module Type	BP SX 150 mc Si	BP 585 LGBC mono Si
Modules	1300	600
Parallel Strings	83	13
Orientation	Shallow tilt; planar arrays	3 roofs; different orientations
Module Standoff	Close to roof	Farther away
PR altering effects	Some shading; High thermal losses	3 orientations; Cool; By lake
Measured Monthly PR	72-80%	~83%

EMPIRICAL MODELLING

A simple model for the system and the PV modules derived from the empirical coefficients can be used to predict the array temperature, V_{DM} and yield as functions of the irradiance, $T_{AMBIENT}$ and wind speed

Figure 5 shows the predicted versus measured performance for one of the strings at array B on a sunny day in May in the UK. Apart from a few spikes in V_{DM} as the inverter started up (before 07:00) there was a good match the rest of the day for V_{DM}, yield and T_{MODULE}.

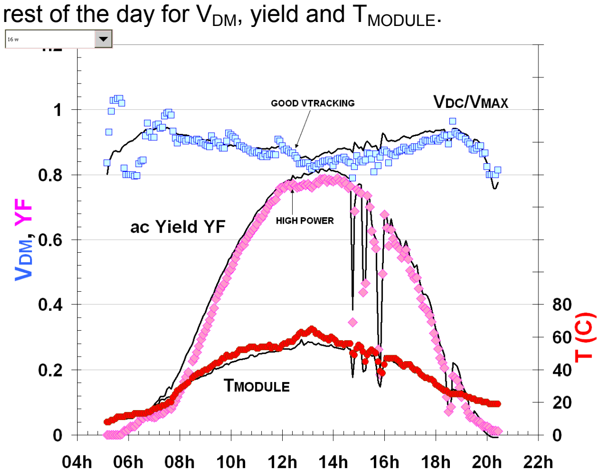

Figure 5 : Measured vs predicted V_{DM}, yield and module temperature for a string performing well in Array B.

Figure 6 shows the performance for another string on the same day. It clearly shows very poor array performance around the middle of the day ($Y << Y_{CALC}$) due to the voltage tracking V_{DM} being too high.

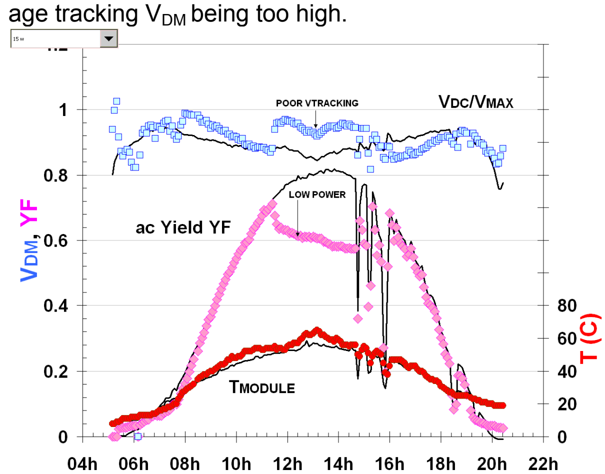

Figure 6 : Measured vs Predicted V_{DM}, yield and module temperature for a string performing poorly in Array B.

On investigation it was found that after installation and commissioning the cooling fans to the inverter on the second string (Figure 6) had failed and the inverter was preventing itself from overheating by deliberately raising its dc voltage to reduce the input power. Late in the afternoon when the irradiance was lower together with the input power, the voltage tracking went back to more normal values. After the cooling fan had been repaired the string went back to performing well, equivalent to the string in figure 5.

SHADING

To ensure optimum performance of a solar array there must be as little shading as possible. However for retrofits on rooftops in urban environments this is not always possible.

An hourly analysis of string currents versus time on bright and cloudy days was carried out on Array A in Australia and lower than expected values of I_{DN} (for part of the day under sunny conditions only) was found on 11 of the 83 strings.

There was no detailed analysis available of possible shading from surrounding buildings or chimneys, vents etc on the retrofit roof. The relative positions of the strings were known and Figure 7 shows the array positions.

Strings with low I_{DN} are identified as “Morn” (shading before 12:00 only), Noon (shading around 12:00) and “Aft” (shading after 12:00 only). The Morn strings are both on the Eastern edge, those marked Aft are on the Western boundary and two marked “Noon” are together on the Northern side of the array. It might be inferred that all of these are due to shading from surrounding buildings or towers.

It is not definite proof but all of the other 72 strings in the grey area in Figure 7 have good I_{DN} values as expected.

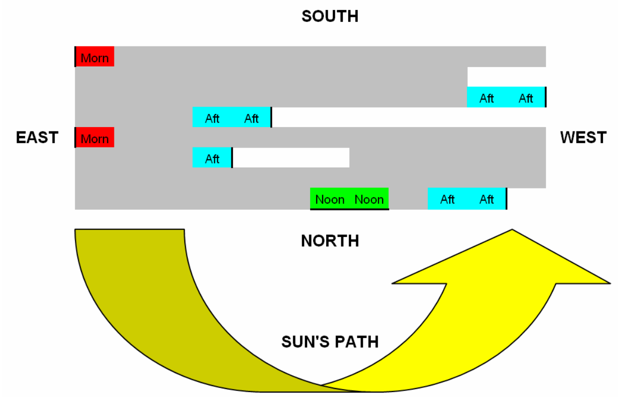

Figure 7 : Top view of Array A in Australia showing the relative positions in the grey array of 11 strings with low I_{DN} at some part of the day and an indication of the sun's path from East to North to West.

CONCLUSIONS

- DC module performance can be characterised by frequent measurements of PF versus irradiance, temperature and wind speed.
- Values of V_{DM} and I_{DM} can be used to determine when the module is performing correctly or if it is wrongly tracking Voltage or shaded.
- Empirical formulae can be used to evaluate the optimum yields of large arrays and to determine any occurrence and reasons for poor performance.
- Shading problems can be analysed even without the details of nearby buildings by looking at the normalised currents and the relative positions of strings on large arrays.

REFERENCES

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[2] J.Wohlgemuth et al.; "Crystalline Silicon Photovoltaic Modules with Anti-Reflective Coated Glass", 31st IEEE PVSC, Orlando 2005.

[3] S Ransome et al: "Can Grid Tied PV systems be characterised with only monthly average values of PR?", 19th PVSEC, Paris 2004 **http://www.bpsolar.com/ContentDocuments/154/5BV_1_56_col.pdf**

[4] IEC 61724 http://www.iec.ch/

Appendix A : Some important normalised parameters, their ranges and definitions used in this study. See [4]

Name		Microsoft Colour number	Long Parameter Name	Unit	Usual Range	Definition	Daily Weighting Σ_t=sum(time)
G_I	□	14 Teal	Plane of array irradiance	kW/m²	0~1.4		
T_{AM}	Δ	44 Gold	Ambient temperature	C	-40~100		$\Sigma_t(T_{AM}*G_I)/\Sigma_t(G_I)$
T_M	o	46 Orange	Module temperature	C	-40~100		$\Sigma_t(T_M*G_I)/\Sigma_t(G_I)$
WS	o	16 Grey –50%	Wind speed	ms^{-1}	0~20?		
YR	□	14 Teal	Insolation or Ref yield	kWh/m²	0~1.4/h	$=\Sigma_t(G_I)$	
V_{DM}	□	41 Light Blue	Normalised DC voltage	-	0~1.4	$=V_{DC}/V_{MAX}$	$\Sigma_t(V_{DM}*G_I)/\Sigma_t(G_I)$
I_{DM}	□	04 Green	Normalised DC current	-	0~1.4/h	$=I_{DC}/I_{MAX}$	
I_{DN}	*	01 Black	Norm. DC current/G_I	-	0~1.4	$=I_{DC}/I_{MAX}/G_I$	
YA	□	39 Lavender	DC yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{DC})/P_{MAX}$	
YF	◊	37 Pale Blue	AC yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{AC})/P_{MAX}$	
ΔT	◊	03 Red	$T_{MODULE}-T_{STC}$	Deg C	-40~100	$=T_M - 25$	
PF	◊	15 Grey –25%	Performance Factor(DC)	-	0~1.4	=YA/YR	
PF_T	Δ	53 Brown	Temp. corrected PF	-	0~1.4	$=PF*(1-\gamma)*\Delta T$	$(\gamma = dP_{MAX}/dT_M)$
PR	□	07 Pink	Performance Ratio (AC)	-	0~1.4	=YF/YR	
kTh	x	01 Black	Instantaneous Clearness Index	-	0.2~0.8	= Global horizontal / Extraterrestrial horizontal irradiance = G0/X0	
Gd/G0	+	56 Grey –80%	Diffuse fraction	-	0.2~1	= Diffuse horizontal / Global horizontal irradiance = Gd/G0	