The Effect of Short-Term Inverter Saturation on PV Performance Modeling

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Introduction

PV projects are generally planned using performance models and hour-averaged solar radiation data to calculate hour-averaged DC power (P_{dc}) output. AC power (P_{ac}) output is then calculated using hourly P_{dc} and a model of inverter performance. Nominal inverter capacities are commonly less than the sum of the PV panels in order to reduce the cost of the PV installation. In this case some of the PV output is lost or "clipped". The inverter clips power instantaneously; therefore calculations that clip hour-averaged P_{dc} will overestimate P_{ac} output during hours in which P_{dc} is greater than the inverter capacity in some minutes and less than the inverter capacity in other minutes. We call this the average-then-clip (AtC) error and it is expected to increase with increasing DC:AC ratios and insolation variability.

AtC errors have been reported by numerous investigators (e.g. Ransome and Funtan 2005). Here we present a multi-site multi-year investigation of AtC errors. Our approach has been to determine AtC errors experimentally:

- Using minute measurement data from PV installations at one site
- Using minute solar measurements and PV_LIB at sites across the US

We then analyzed these results to determine the effect on AtC error of DC:AC ratio, PV installation type; annual, seasonal, and time of day meteorology.

AtC Error

Minute-scale PV output data were used to calculate Clip then Average AC power output was calculated as

$$\overline{P_{ac,CtA}} = \frac{1}{n}\sum_{i=1}^{n} f(P_{dc,i}, V_{dc,i})$$

where
n - minutes
f - inverter model
$P_{dc,i}$ - minute DC power
$V_{dc,i}$ - minute DC voltage

Average then Clip AC power output was calculated as

$$\overline{P_{ac,AtC}} = f(\overline{P_{dc}}, \overline{V_{dc}})$$

where
$\overline{P_{dc}}$ - hour DC power
$\overline{V_{dc}}$ - hour DC voltage

The relative error due to averaging then clipping, the AtC error, was calculated as

$$\delta = \frac{\overline{P_{ac,AtC}} - \overline{P_{ac,CtA}}}{\overline{P_{ac,CtA}}} \times 100$$

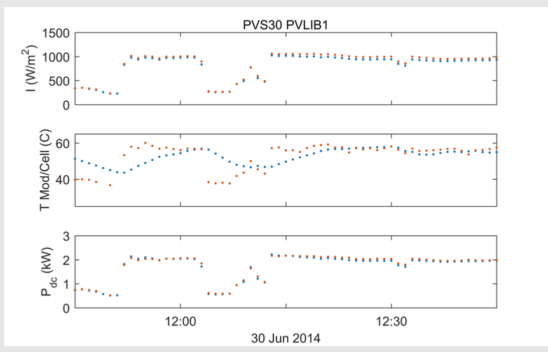
PV Modeling

PV modeling was done using PV_LIB v 1.32 and this model chain:

- Radiation - Perez et al. 1990
- PV Panel Electrical - Sandia Single Diode with Parameters from CEC database
- PV Panel Thermal – Sandia, Values for Si Module from King et al. 2004
- Losses - NREL SAM
- Inverter - Sandia (King et al. 2007), Parameters from NREL database

Minute-scale Thermal Model

Actual module temperature changes lag modeled ones due to thermal mass (e.g. Armstrong and Hurley 2010). See figure where blue is measured and red is modeled. Thermal model was adjusted to use the 10-min running average of modeled temperature.



AtC Error Using Measurements

Data

Minute-scale P_{dc} was measured at the Southeastern Solar Research Center (SSRC) in Birmingham AL. The site included five PV installations, each with 10 multicrystalline PV modules and an oversized inverter (DC:AC ratio = 0.8). The PV installations were:

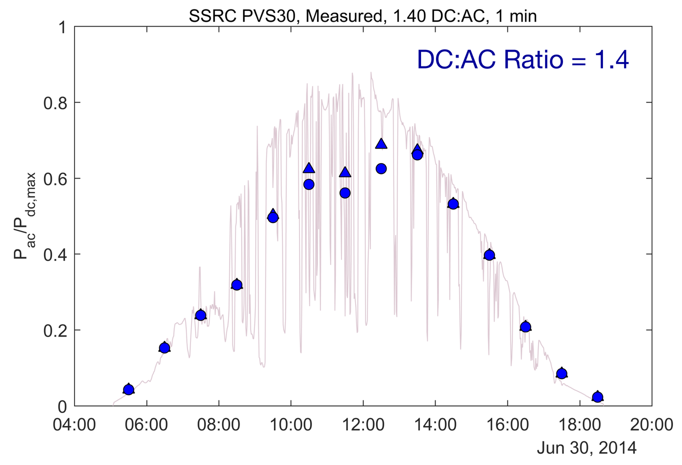
- South-facing 30° tilt (PVS30)
- South-facing 10° tilt (PVS10)
- Southwest-facing 30° tilt (PVS30)
- Single-axis tracking (PV1Axis)
- Dual-axis tracking (PV2Axis)

Analysis

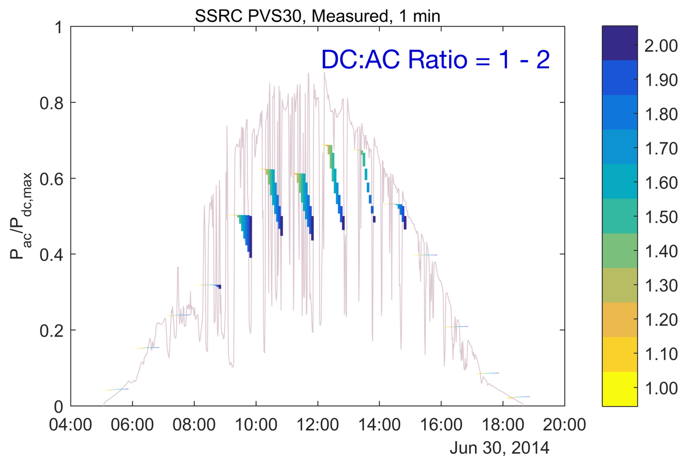
P_{ac} was calculated from measured P_{dc} and the Sandia inverter model. Inverter parameters were adjusted to simulate DC:AC ratios of 1.0 – 2.0. This ratio was the nominal DC capacity of the PV modules divided by the nominal AC capacity of the inverter.

Results

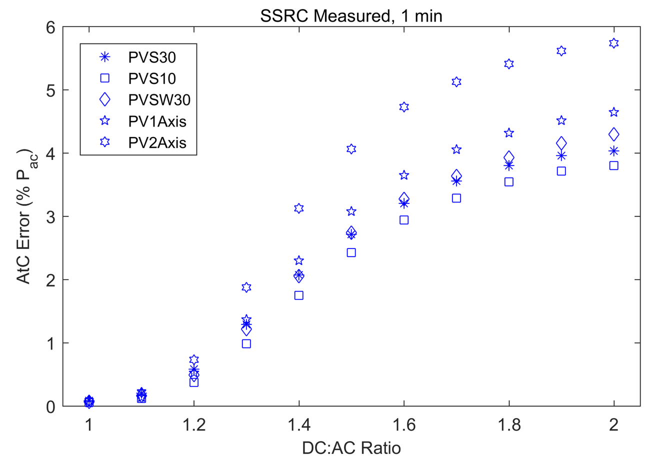
- AtC error 0 – 5.7%; depended on mount and DC:AC ratio
- AtC error 2.1 – 3.1% for DC:AC = 1.4
- AtC error using P_{dc} from PV_LIB was within 10% of AtC error using measured P_{dc}



Minute-scale P_{ac} (line), Average then Clip P_{ac} (triangle), and Clip then Average P_{ac} (circle) at the SSRC site.



Minute-scale Pac (line), Average then Clip Error (colored line) for a range of DC:AC ratios at the SSRC site.



Average then Clip Error as a function of PV installation and DC:AC ratio at the SSRC site.

AtC Error Using Solar Measurements and PV_LIB

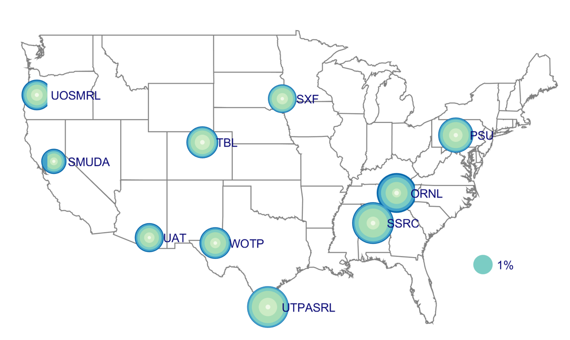
Data

Minute-scale solar radiation from SURFRAD, MIDC, and EPRI members was used with PV_LIB to calculate minute-scale P_{dc}. Calculations used 1-7 years of data, depending on site. The PV installations were:

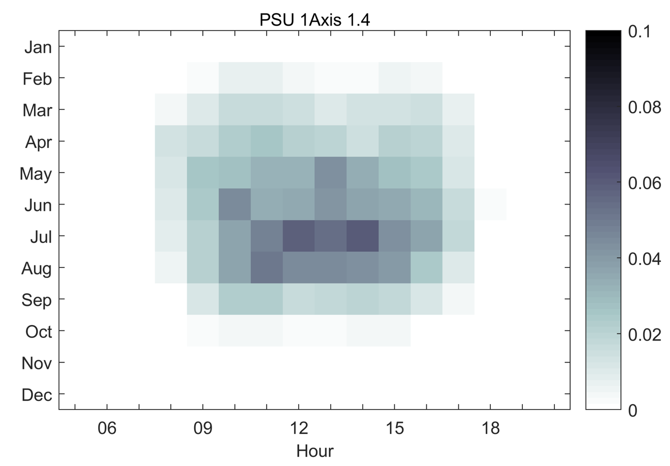
- South-facing 25° tilt (PVS25)
- Single-axis tracking (PV1Axis)

Analysis

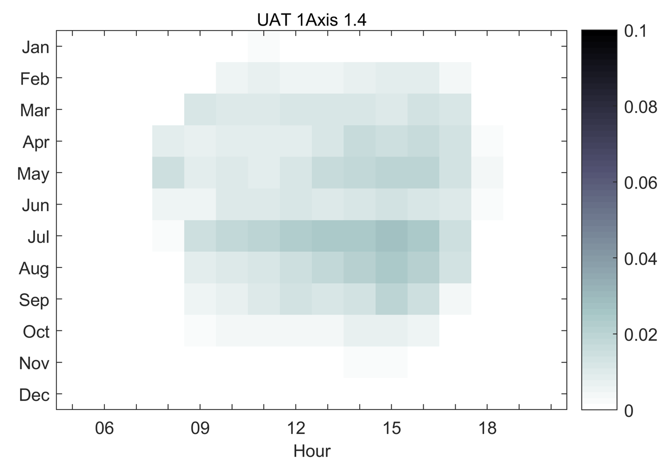
P_{ac} was calculated from modeled P_{dc} and the Sandia inverter model. Inverter parameters were adjusted to simulate DC:AC ratios of 1.0 – 2.0. This ratio was the nominal DC capacity of the PV modules divided by the nominal AC capacity of the inverter.



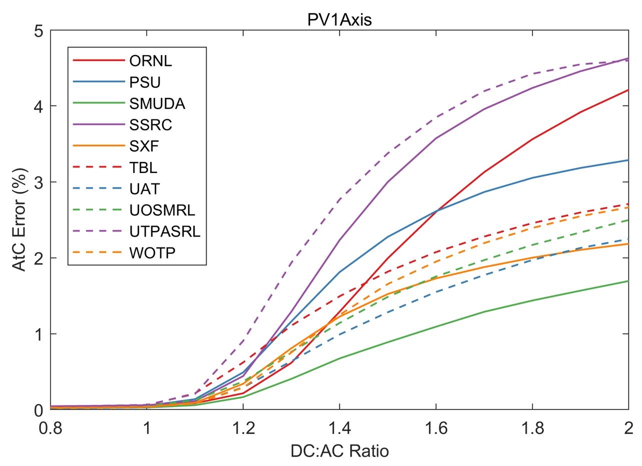
Concentric circles show AtC error at the sites for DC:AC ratios = 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0.



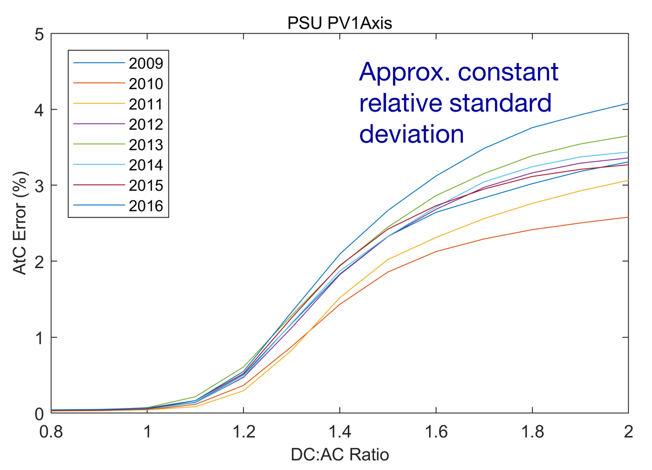
Contribution to aggregate AtC error for each month-hour at the Penn State site with DC:AC = 1.4.



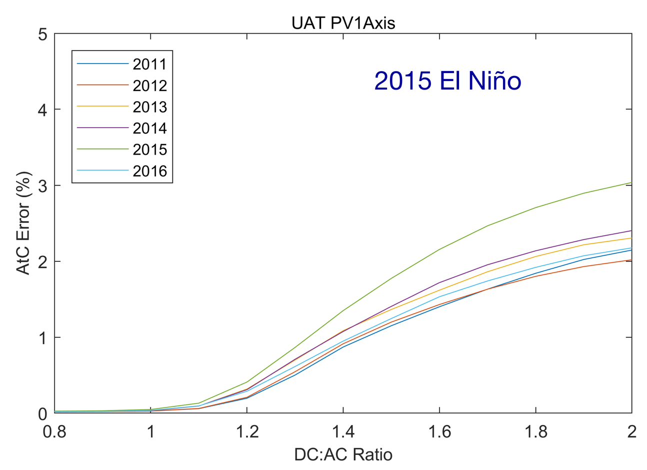
Contribution to aggregate AtC error for each month-hour at the Univ. Arizona Tucson site with DC:AC = 1.4.



Aggregate AtC error for 10 sites as a function of DC:AC ratio. See map above for site key.



Aggregate AtC error by year as a function of DC:AC ratio at the Penn State site.



Aggregate AtC error by year as a function of DC:AC ratio at the Univ. Arizona Tucson site.

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Conclusions

The AtC error artificially increases PV output modeled using hourly inputs by as much as 4.5% for high DC:AC ratios.

The AtC error can be accurately estimated using minute-scale inputs to PV models.

The AtC error:

- Increases with DC:AC ratio;
- Is affected by mounting type with 2 Axis > 1 Axis > Fixed at latitude tilt > Fixed at shallow tilt;
- Is affected by climate with Humid Subtropical > Mediterranean, Desert;
- Is somewhat variable across years;
- Affected by month-hour, and this varies with climate.

Having shown that the AtC error is significant, and that we can model it using minute-scale measurements, we aim to generalize our approach so that AtC errors may be calculated from hourly inputs, e.g. TMY input files. Our proposed approach is to synthesizing minute-scale solar radiation time series from hourly time series. Once this is done, we aim to provide software to the community so that corrections to the AtC error may be incorporated in PV modeling packages.

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