pvfit.app

Getting Started with PVfit

Mark Campanelli, PhD

mark.campanelli@gmail.com
Intelligent Measurement Systems LLC, Bozeman MT USA
https://github.com/markcampanelli/pvpmc2024/tutorial

May 2024

Tutorial Overview

Setup & Preliminaries

Python Environment and Package Installation

Set up a Python 3.10-12 virtual environment—

```
$ python -V
Python 3.11.7
$ python -m venv pvfit_pvpmc2024
$ . pvfit_pvpmc2024/bin/activate
$ python -m pip install --upgrade pip setuptools
```

Install `pvfit v0.0.1` from PyPI with `demo` dependencies—

```
$ python -m pip install pvfit[demo]==0.0.1
$ python -c "from pvfit import __version__; \
print(__version__)"
0.0.1
```

Tutorial Notebook Setup

Install `jupyterlab` for interactive tutorials—

```
$ python -m pip install jupyterlab
```

Run `jupyterlab` within a web browser (or VSCode, etc.)—

```
$ jupyter lab
```

This presentation follows these Jupyter notebooks from `https://github.com/markcampanelli/pvpmc2024/tutorial`—

- `1_single_diode_model_calibration.ipynb`
- `2_dc_performance_prediction.ipynb`
- `3_flex_your_model!.ipynb`

Design Patterns and Usage Notes

- `pvfit` has not yet reached stable v1.0. For latest, visit `https://github.com/markcampanelli/pvfit`.
- Objects encapsulate immutable data (validation in initializer).
- Functions transform data from input object to output object.
- Functions/methods/initializers take named arguments—
  `result = fit(iv_performance_matrix=my_matrix)`
- Functions return multple values in dictionaries.
- Variable names typically include units, e.g., `I_sc_A`.
- The minimal library requires only `numpy` and `scipy`.
- Vectorization used wherever practicable.

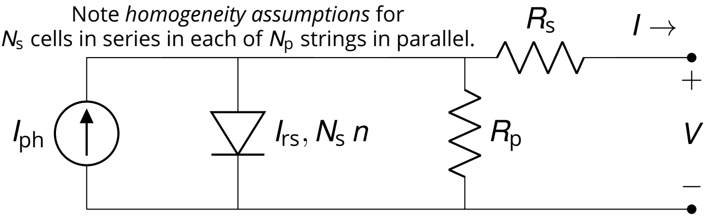
Single-Diode Model Calibration

Single-Diode Equation (SDE)

The current-voltage (I-V) relationship of a photovoltaic (PV) device at fixed irradiance and temperature can be modeled by—

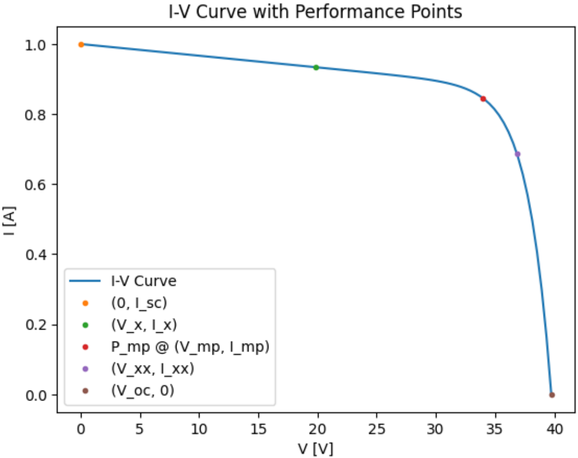
$$I = I_{\mathrm{ph}} - I_{\mathrm{rs}} \left(e^{q \frac{V + I R_{\mathrm{s}}}{N_{\mathrm{s}} n k_{\mathrm{B}} T}} - 1 \right) - \underbrace{G_{\mathrm{p}}}_{=1/R_{\mathrm{p}}} (V + I R_{\mathrm{s}}) \qquad \text{(SDE)}$$

Note *homogeneity assumptions* for N_{s} cells in series in each of N_{p} strings in parallel.



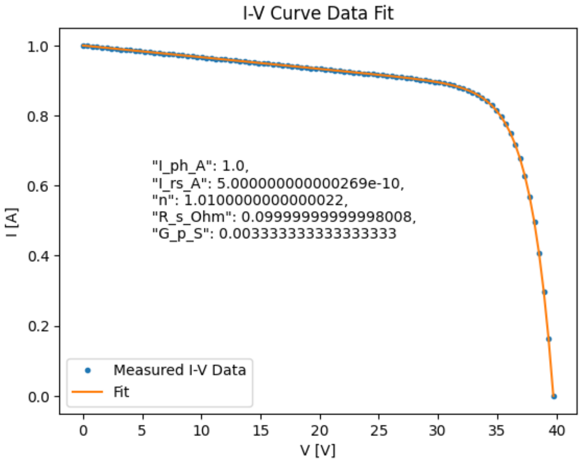
Solving the SDE: Forward Problem

Given SDE parameters I_{ph}, I_{rs}, n, R_{s}, and G_{p}, compute I-V curve.



Solving the SDE: Inverse Problem

Given measured *I-V* curve data, estimate the SDE parameters.



Single-Diode Model (SDM) from Auxiliary Equations

Which SDE parameters depend on irradiance and/or temperature?

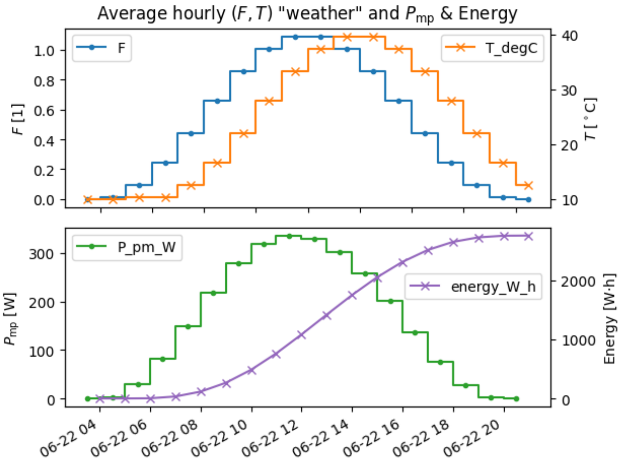
$$
\begin{aligned}
I_{\mathrm{rs}} &= I_{\mathrm{rs}0} \left(\frac{T}{T_0} \right)^3 e^{\frac{E_{\mathrm{g}0}}{n_0 k_{\mathrm{B}2}} \left(\frac{1}{T_0} - \frac{1}{T} \right)}, \\
I_{\mathrm{ph}} &= I_{\mathrm{rs}} \left(e^{q \frac{I_{\mathrm{sc}} R_{\mathrm{s}}}{N_{\mathrm{s}} n k_{\mathrm{B}1} T}} - 1 \right) + \left(G_{\mathrm{p}} \, R_{\mathrm{s}} + 1 \right) I_{\mathrm{sc}}, \\
I_{\mathrm{sc}} &= F \, I_{\mathrm{sc}0}, \quad n = n_0, \quad R_{\mathrm{s}} = R_{\mathrm{s}0}, \quad G_{\mathrm{p}} = G_{\mathrm{p}0},
\end{aligned}
\tag{SDM}
$$

with six *unobservable* model parameters at STC—

$I_{\mathrm{sc}0}$: short-circuit current [A],
$I_{\mathrm{rs}0}$: reverse-saturation current [A],
n_0 : diode ideality factor [·],
$R_{\mathrm{s}0}$: series resistance [Ω],
$G_{\mathrm{p}0}$: parallel conductance [S],
$E_{\mathrm{g}0}$: material bandgap [eV].

Solving the SDM: Forward Problem

Given calibrated SDM and (F, T) time series, compute P_{mp}.



Solving the SDM: Inverse Problem I

I_{sc}, P_{mp}, V_{mp}, and V_{oc} reported according to IEC 61853-1[1] at the following operating conditions—

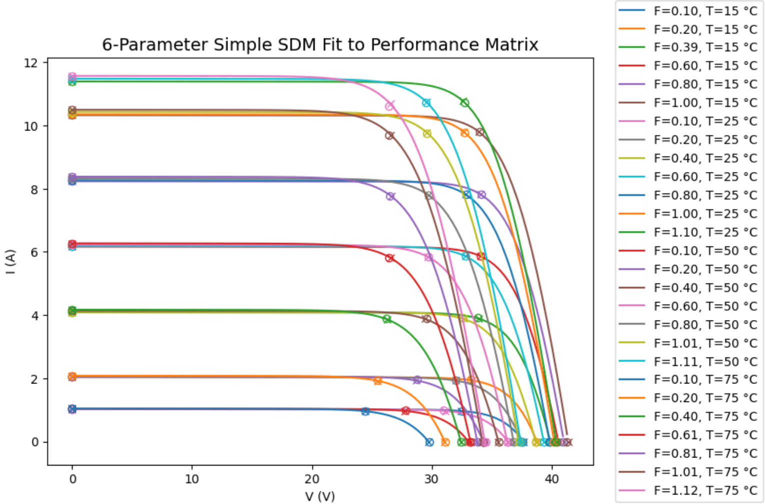
		G [W/m²]						
		100	200	400	600	800	1000	1100
T [°C]	75	○	○	○	●	●	●	●
	50	○	○	●	●	●	●	●
	25	●	●	●	●	●	●	●
	15	●	●	●	●	●	●	○

Given such performance-matrix data, estimate SDM parameters—

I_{sc0}, I_{rs0}, n_0, R_{s0}, G_{p0}, and E_{g0}.

[1] ● indicates required, ○ indicates optional; STC spectrum w/normal irradiance

Solving the SDM: Inverse Problem II



Solving the SDM: Inverse Problem — Limited Data I

PVfit can fit the SDM to limited data from a specification datasheet.

Three performance points from I-V curve at STC—

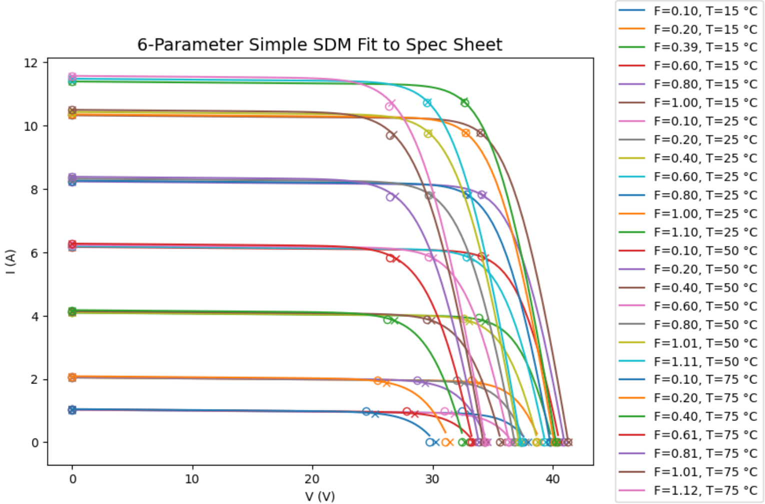
$$(0, I_{\mathrm{sc}0}),\ (I_{\mathrm{mp}_0}, V_{\mathrm{mp}_0}),\ \text{and}\ (V_{\mathrm{oc}0}, 0),$$

with three temperature coefficients at STC—

$$\alpha_{I_{\mathrm{sc}0}},\ \gamma_{P_{\mathrm{mp}_0}},\ \text{and}\ \beta_{V_{\mathrm{oc}0}}.$$

- Fit quality is typically reduced.
- Be careful fitting a SDM that is not well informed by data, e.g., a photoconductive shunt $G_\mathrm{p} = F\, G_{\mathrm{p}_0}$ when spec sheet lacks data about performance w.r.t. effective irradiance ratio F.

Solving the SDM: Inverse Problem — Limited Data II



DC Performance Prediction

Determining Cell Temperature T

PVfit's SDM presumes model calibration w.r.t. *cell* temperature T.

Several model options to choose from (thanks `pvlib-python`!).

E_{POA} computed using Perez model. Parameters U_0 and U_1 may be installation specific, while ΔT is not typically measured—

- Ambient to back-of-module temperature—

$$T_{\mathrm{m}} = T_{\mathrm{a}} + \frac{E_{\mathrm{POA}}}{U_0 + U_1 \times WS} \qquad \text{(Faiman)}$$

- Back-of-module to cell temperature—

$$T = T_{\mathrm{m}} + \frac{E_{\mathrm{POA}}}{E_0} \Delta T \qquad \text{(SAPM)}$$

Recall homogeneity, and also here steady-state, assumptions.

Determining Effective Irradiance Ratio F

- Reference PV device (matched temp's & angular responses)—

$$F = \frac{I_{\mathrm{sc}}}{I_{\mathrm{sc}0}} = \overbrace{M(T, T_0)}^{=1 \text{ when matched}} \frac{I_{\mathrm{sc,ref}}}{I_{\mathrm{sc,ref}_0}} = \frac{\int_{\lambda=0}^{\infty} S(\lambda, T)\, E_\lambda(\lambda)\, d\lambda \int_{\lambda=0}^{\infty} S_{\mathrm{ref}}(\lambda, T_0)\, E_{\lambda,0}(\lambda)\, d\lambda}{\int_{\lambda=0}^{\infty} S(\lambda, T_0)\, E_{\lambda,0}(\lambda)\, d\lambda \int_{\lambda=0}^{\infty} S_{\mathrm{ref}}(\lambda, T)\, E_\lambda(\lambda)\, d\lambda}$$

- Sandia Array Performance Model (SAPM)—

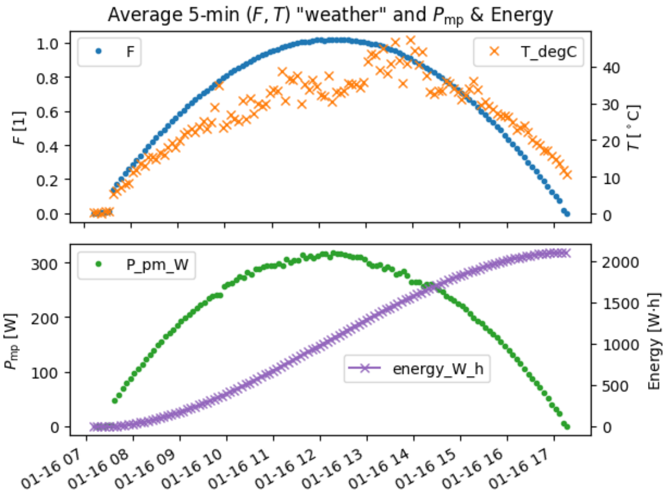
$$F = \frac{I_{\mathrm{sc}}}{I_{\mathrm{sc}0}} = \overbrace{f_1 \frac{f_2\, E_{\mathrm{b}} + f_{\mathrm{d}}\, E_{\mathrm{d}}}{E_0}}^{\text{Effective irradiance } E_{\mathrm{e}}} \left(1 + \alpha_{\mathrm{sc}0}\, (T - T_0)\right)$$

- PVfit's Spectral+Angular-Diffuse Correction—

$$F = \frac{I_{\mathrm{sc}}}{I_{\mathrm{sc}0}} = \frac{\int_{\lambda=0}^{\infty} S(\lambda, T_0)\, E_{\lambda,\mathrm{eff}}(\lambda)\, d\lambda}{\int_{\lambda=0}^{\infty} S(\lambda, T_0)\, E_{\lambda,0}(\lambda)\, d\lambda} \left(1 + \alpha_{\mathrm{sc}0}\, (T - T_0)\right)$$

with $\displaystyle\int_{\lambda=0}^{\infty} E_{\lambda,\mathrm{eff}}(\lambda)\, d\lambda = E_{\mathrm{eff}}$ (sum of IAM-corrected POA-irradiance components)

A Realistic DC Performance Prediction



Flex Your Model!

New Opportunities from a Well–Calibrated SDM

We've paid good money for the IEC 61853-1 measurements to fit our SDM, so let's make good use of it.

The F formulation bridges a gap between the calibration laboratory and traditional MET-station methodologies—

- Soiling measurements often provide a reference PV device, which could infer F and T, perhaps more accurately and less expensively, esp. if matched. (So, about that unknown $\Delta T \ldots$)
- Tune satellite-based models directly to ground-based, PV-derived (F, T) time series—Look Mom, No MET Station!.
- Incorporate degradation into a minimally sufficient SDM?
- Other ideas welcome! Send to `mark.campanelli@gmail.com`.

(F, T) from a PV-Based MET Station I

Recall the simple SDM—

$$I = I_{\mathrm{ph}} - I_{\mathrm{rs}} \left(e^{q \frac{V + I\,R_{\mathrm{s}}}{N_s\, n\, k_{\mathrm{B1}}\, T}} - 1 \right) - G_{\mathrm{p}} \left(V + I\,R_{\mathrm{s}} \right)$$

$$I_{\mathrm{rs}} = I_{\mathrm{rs0}} \left(\frac{T}{T_0} \right)^3 e^{\frac{E_{\mathrm{g}0}}{n_0 k_{\mathrm{B2}}} \left(\frac{1}{T_0} - \frac{1}{T} \right)},$$

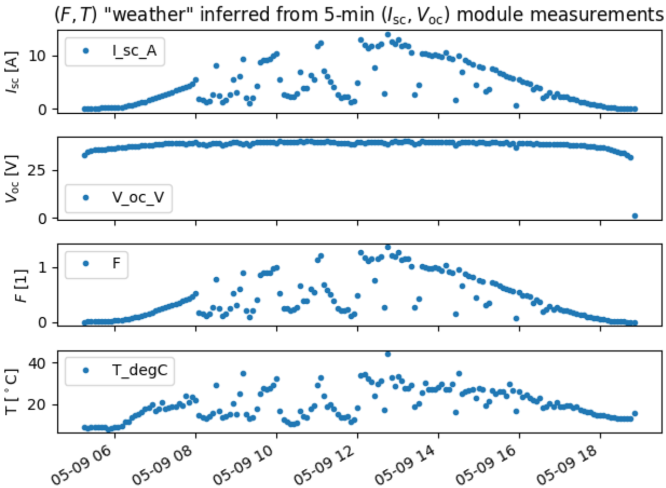
$$I_{\mathrm{ph}} = I_{\mathrm{rs}} \left(e^{q \frac{I_{\mathrm{sc}} R_{\mathrm{s}}}{N_s n k_{\mathrm{B1}} T}} - 1 \right) + \left(G_{\mathrm{p}} R_{\mathrm{s}} + 1 \right) I_{\mathrm{sc}},$$

$$I_{\mathrm{sc}} = F\, I_{\mathrm{sc0}}, \quad n = n_0, \quad R_{\mathrm{s}} = R_{\mathrm{s0}}, \quad G_{\mathrm{p}} = G_{\mathrm{p}0},$$

Suppose we calibrate this for a reference PV module, then measure two sufficiently separated I-V points.

This is typically enough to infer F & T, i.e., a PV-based MET station.

(F, T) from a PV-Based MET Station II



The End...or the Beginning?

Thanks for trying PVfit!

- Could you integrate PVfit into your modeling workflow?
- Could you integrate PVfit into your measurement systems?
- How could you better flex your model?

Open-source software isn't free.

Perhaps you have funding to support the effort?

`mark.campanelli@gmail.com`