Overview of Photovoltaic Module Performance Modeling Approaches

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PV Module Modeling Approaches

- **Equivalent Circuit Models**
  - Describe full I-V curve at desired irradiance and temperature conditions
  - Single diode equation ('5 parameter') is most common
  - Auxiliary equations relate the 5 parameters to irradiance and temperature
    - Different among PVsyst, De Soto, CEC, PV*SOL

- **Point Models**
  - Describe cardinal points on the IV curve: Pmp, Imp, Vmp, Isc, Voc
  - PVWatts
  - Huld model
  - Sandia PV Array Performance Model (SAPM)
  - Loss Factors Model

- **‘Data’ Models**
Module model is only one part of a modeling process.

“Single Diode” Models

- CEC, PVsyst, CEC, PV*SOL, others
  - IV curve described by single diode equation
  - “5 parameters” – for each IV curve

- Auxiliary equations describe how ‘5 parameters’ change with irradiance, temperature
  - Different equations for each PV model
  - Auxiliary equations contain the model parameters
  - E.g., De Soto model has 7 parameters, PVsyst v6 has 9 parameters

\[
I = I_L - I_0 \left[ \exp \left( \frac{V + I R_s}{n V_T} \right) - 1 \right] - \frac{V + I R_s}{R_{sh}}
\]

\[
I_L (E, T_C) = \frac{E}{E_0} \left[ I_{L0} + \alpha_{isc} (T_C - T_0) \right]
\]

\[
I_O = I_{O0} \left( \frac{T_C}{T_0} \right)^3 \exp \left( \frac{1}{k} \left( \frac{E_{g0}}{T_0} - \frac{E_g (T_C)}{T_C} \right) \right)
\]

\[
R_{sh} = R_{sh0} \frac{E_0}{E}
\]

De Soto et al, 2006
## Ancillary Equations

<table>
<thead>
<tr>
<th>Diode equation term (unit) symbol</th>
<th>PVsyst v6</th>
<th>CEC ‘6 parameter’ model</th>
</tr>
</thead>
<tbody>
<tr>
<td>light current (A) $I_L$</td>
<td>$I_L(E,T_C) = \frac{E}{E_0} I_{L0} + \alpha_{Isc} (T_C - T_0)$</td>
<td>$I_L(E,T_C) = \frac{E}{E_0} [I_{L0} + \alpha'_{Isc} (T_C - T_0)]$</td>
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<tr>
<td></td>
<td></td>
<td>$\alpha'<em>{Isc} = \alpha</em>{Isc} (1 - \text{Adjust}/100)$</td>
</tr>
<tr>
<td>dark current (A) $I_O$</td>
<td>$I_O(T_C) = I_{O0} \left[\frac{T_C}{T_0}\right]^3 \exp\left[\frac{q\varepsilon_C}{k\gamma} \left(\frac{1}{T_0} - \frac{1}{T_C}\right)\right]$</td>
<td>$I_O(T_C) = I_{O0} \left[\frac{T_C}{T_0}\right]^3 \exp\left[\frac{1}{k} \left(\frac{E_g(T_0)}{T_0} - \frac{E_g(T_C)}{T_C}\right)\right]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_g(T_C) = E_{g0} \left(1 - 0.0002677(T_C - T_0)\right)$</td>
</tr>
<tr>
<td>series resistance (Ω) $R_S$</td>
<td>$R_S = R_{S0}$</td>
<td>$R_S = R_{S0}$</td>
</tr>
<tr>
<td>shunt resistance (Ω) $R_{SH}$</td>
<td>$R_{SH} = R_{SH,\text{base}} + (R_{SH,0} - R_{SH,\text{base}}) \exp\left(-R_{SH}\exp\frac{E}{E_0}\right)$</td>
<td>$R_{SH}(E) = R_{SH0} \frac{E_0}{E}$</td>
</tr>
<tr>
<td></td>
<td>$R_{SH,\text{base}} = \max \left[\frac{R_{SH,\text{ref}} - R_{SH,0}}{1 - \exp(-R_{SH,\exp})}, 0\right]$</td>
<td></td>
</tr>
<tr>
<td>ideality factor (unitless) $\gamma$ or $n$</td>
<td>$\gamma = \gamma_0 + \mu_\gamma (T_C - T_0)$</td>
<td>$n = n_0$</td>
</tr>
</tbody>
</table>
Open issues with diode models

- Simulated IV curves often don’t match measurements at low irradiance
- Methods to estimate model parameters are often not carefully scrutinized
  - Many methods return non-physical values, e.g., $n < 1$
  - As a consequence, the same data lead to different parameter sets
  - Could have reference cases to test estimation methods (a common practice in other disciplines)
- Can we validate the auxiliary equations?
  - Light, dark current forms derive from device physics
  - Others are eyeballed from data (e.g., $R_{SH}$ in CEC model)
  - May involve corrections to match IV curves (e.g., $\gamma$ in PVsyst v6)
  - Equations for $R_s$, $n$ or $\gamma$ are most promising targets
Single Point Models

- **PVWatts**: 
  \[ P_{dc} = \frac{I_{tr}}{1000} P_{dc0} (1 + \gamma (T_{cell} - T_{ref})) \]

- **Huld Model**: 
  \[ P(G', T') = G' (P_{STC,m} + k_1 \ln(G') + k_2 \ln(G')^2 + k_3 T' + k_4 T' \ln(G') + k_5 T' \ln(G')^2 + k_6 T'^2) \]

- **PVUSA**: 
  \[ P = I \cdot (A + B \cdot I + C \cdot T_a + D \cdot WS) \]
  - Because \( P \) is \( P_{AC} \), PVUSA combines cell temperature and inverter efficiency model with module performance model

- PVWatts is (almost) module-agnostic: the only term which derives from measurement is the temperature coefficient \( \gamma \)
- PVUSA is not a module model per se; it’s a whole system model
- Huld model is intended to be fit to common measurements: back-of-module temperature and broadband plane-of-array
The Sandia Array Performance Model

- Describes module output at SC, OC and MP points
- As a function of beam and diffuse irradiance \( (E_b \text{ and } E_{\text{diff}}) \), cell temperature \( (T_C) \), air mass \( (AM_a) \) and angle of incidence \( (AOI) \)
- 14 empirical coefficients, 2 empirical functions \( (f_1 \text{ and } f_2) \)
- With exception of \( f_2 \), coefficients must be determined for individual modules

\[
V_{OC} = V_{OC0} + N_S n \delta(T_C) \ln(E_e) + \beta_{OC}(T_C - T_0)
\]

\[
V_{MP} = V_{MP0} + C_2 N_S n \delta(T_C) \ln(E_e) + C_3 N_S (n \delta(T_C) \ln(E_e))^2 + \beta_{MP}(T_C - T_0)
\]

\[
I_{SC} = I_{SC0} f_1(AM_a) E_e \left(1 + \alpha_{SC}(T_C - T_0)\right)
\]

\[
I_{MP} = I_{MP0} \left(C_0 E_e + C_1 E_e^2\right) \left(1 + \alpha_{MP}(T_C - T_0)\right)
\]

\[
E_e = E_b f_2(AOI) + E_{\text{diff}} f_d
\]
Six Normalized LFM Variables

1. \( n_{IscT} = \)
2. \( n_{Rsc} = \)
3. \( n_{Imp} = \)
4. \( n_{Vmp} = \)
5. \( n_{Roc} = \)
6. \( n_{VocT} = \)

Current factors

Voltage factors

\[
nf(G_i) = c_1 + c_2 \log(G_i) - c_3 \times G_i^2
\]

\[
T_{CORR,Isc} = 1 + \alpha_{Imp} \times (25 - T_c)
\]

\[
T_{CORR,Voc} = 1 + \beta_{Vmp} \times (25 - T_c)
\]

MMF = spectral mismatch, \( G_i \) = irradiance
‘Data’ models

- These models are based directly on measure data (e.g., 61853-1) or outdoor IV curves collected over time or trained on these data.
- Models describe how to interpolate and extrapolate from a measured reference data set.
  - *Janine Freeman* will describe one such model developed at NREL.
  - These models do not have parameters but rather are descriptions of a procedure that results in a result.
- Another type of “Data” model is Machine Learning
  - *Birk Jones* from Sandia has used a Gaussian Process Regression algorithm to simulate IV curves
Issues common to all performance models

- Parameter estimation is generally not transparent nor reproducible
- Data requirements are not well understood:
  - Thought to be either:
    - Minimal, e.g., fit a diode model using single IV curve and a temperature coefficient, or
    - Extensive, e.g., requiring days of measurements outdoors on a two-axis tracker
  - Both are wrong
  - 61853-1 is enough for diode or point models, with the exception of the spectral mismatch function
- Multiple models in use but underlying data is not shared
  - Some resort to creating “models of models”, e.g., fitting the SAPM to a PVsyst simulation
  - A modeled model inherits the problems of the source model
Useful Module Model Characteristics

- Parameters are easy/straightforward to obtain
  - Standards exist for the collection of the characterization data
  - Calculations yield consistent parameter values (solutions are unique)
  - Estimation is transparent and reproducible from a common data set
  - Parameter values are easily shared and published
  - Values of parameters with physical meaning do not violate physics

- Model predicts performance well across the entire range of environmental conditions
  - High and low irradiance
  - High and low temperatures
  - Spectral effects
Questions?

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