Early Life PV System Degradation Evaluation and Modeling Based on Cumulative Exposure to Environmental Stressors

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Overview

1. Motivation

2. Proposed Concept

3. Test PV Plants

4. Degradation Stressor Identification

5. Degradation Modeling

6. Conclusion/Future work
Motivation

1. Identify dominate stressor for particular module
   a. Data-driven approach?

2. Decrease model error caused by degradation
   a. Method to account for degradation?
   b. Example Problem:
      • PV System in New Mexico
      • Percent Difference:
        o \( \%\text{Diff} = \frac{E_{\text{Actual}} - E_{\text{Model}}}{E_{\text{actual}}} \)
      • -3% Diff. After Year 5
      • % Difference Increase = \( \sim 0.6\% / \text{year} \)
Hypothesis: Cumulative Exposure evaluation methodology can identify stressors and improve multi-year models.

1. Measure/Collect
   a) Climate
   b) PV Performance

2. Quantify
   a) Exposure (amount of stress)
   b) Performance Changes (loss in output)

3. Analyze - Identify dominate stressor using data

4. Model - Predict degradation based on ..
   a) Performance in different location
      a) e.g. performance in FL can be used to predict degradation in NM
   b) Indoor accelerated testing results
      a) e.g. use indoor test results to predict degradation
Test PV Plants
Test PV Plants – Sensors & Locations

Systems

1. Regional Test Center Reference
   (pv-dashboard.sandia.gov)
2. Size: ~3.4 kW
3. 12 Modules in Series
4. Suniva OPT270 Black

Locations

1. New Mexico
2. Florida
3. Nevada
4. Vermont

Sensors

1. DC Current & Voltage
2. Plane of Array Irradiance
Data Analysis Methodology: Preprocess

1. Translation

\[ I_o = \frac{E_o}{E} \left( \frac{I_{\text{actual}}}{1 + \alpha(T_m - T_o)} \right) \]

\[ V_o = \left( \frac{V_{\text{actual}}}{1 + \beta(T_m - T_o)} \right) \]

2. Data Quality Filter: Z-Score

\[ Z_{P,i} = \left[ \frac{Y_{P,i} - M_P}{|MAD|} \right] \]

where:

- \( Y_{P,i} \) parameter at time \( i \),
- \( M_P \) the median, and
- \( |MAD| \) the median of the absolute deviation
Data Analysis Results: Time-Based Analysis

**Translated Max Power Point Current**

- **New Mexico**
- **Florida**
- **Nevada**
- **Vermont**

**Translated Max Power Point Voltage**

- **New Mexico**
- **Florida**
- **Nevada**
- **Vermont**
Data Analysis Methodology – Stressor Exposure

3. Compute Stressor Exposure
   - Thermal Cycling [1]
     \[ CS_{\Delta T} = \sum_{t=0}^{n} (\Delta T_m(t)) \exp\left(\frac{-Q_a}{k_B T_m(t)}\right) \]
   - Wind Load
     \[ CS_{\text{wind}} = \sum_{t=0}^{n} (P_{\text{wind}}(t)) \exp\left(\frac{-Q_a}{k_B T_m(t)}\right) \]
   - Humidity [2]
     \[ CS_{\text{h}} = \sum_{t=0}^{n} (A) \exp\left(\frac{-Q_a}{k_B T_m(t)}\right) R_H(t)^n \]
   - Radiation [3]
     \[ CS_{\text{rad}} = \sum_{t=0}^{n} (E(t)) \exp\left(\frac{-Q_a}{k_B T_m(t)}\right)(0.05) \]
   - Temperature [4]
     \[ CS_{\text{temp}} = \sum_{t=0}^{n} (T_m(t)) \exp\left(\frac{-Q_a}{k_B T_m(t)}\right) \]

4. Least-Squares Analysis
   - Compute slopes
   - Compare slopes
Data Analysis Results: Stressor-Based Analysis

1. System Current Least-Square Reg. Slopes
   1. Time: Similar
   2. Stressor-Based: Similar w/ Cumulative Temperature

2. System Voltage Least-Square Reg. Slopes
   1. Time-Based: Variation among sites
   2. Stressor-Based: Similar w/ Temp. Cycling

### Time-Based Slopes

<table>
<thead>
<tr>
<th></th>
<th>NM</th>
<th>FL</th>
<th>NV</th>
<th>VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>-0.01</td>
<td>-0.13</td>
<td>-0.05</td>
<td>-0.026</td>
</tr>
<tr>
<td>Voltage</td>
<td>-0.26</td>
<td>-0.58</td>
<td>-0.03</td>
<td>-0.67</td>
</tr>
</tbody>
</table>

### Stressor-Based Slopes

<table>
<thead>
<tr>
<th></th>
<th>NM</th>
<th>FL</th>
<th>NV</th>
<th>VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current vs Temp</td>
<td>-0.018</td>
<td>-0.018</td>
<td>-0.028</td>
<td>-0.13</td>
</tr>
<tr>
<td>Voltage vs Temp</td>
<td>-0.002</td>
<td>-0.0017</td>
<td>-0.001</td>
<td>-0.006</td>
</tr>
</tbody>
</table>

**Current vs Cumulative Temperature**

**Voltage vs Cumulative Temp. Cycling**
Degradation Models Methodology: Outdoor Data

1. $P_{\text{model}} = \text{SAPM} + \text{Degradation}$
   - Sandia Array Performance Model (SAPM)
   - Linear Degradation $= f(\text{stressor})$

2. Time-Based Model
   - Assume 0.5%/year

3. Stressor-Based Model
   - Model NM system based on FL results
Degradation Models Results: Outdoor Data

1. No Degradation Model
   1. Error = 1.4%

2. Time-Based Degradation Model
   1. Error = 0.57%

3. Stressor-Based Degradation Model
   1. Error = 0.45%
Data Measurement/Analysis Discussion

What caused change in voltage?

Pre and Post I-V Curves were similar

Little change in Voltage and some change in Current
Conclusion/Future Work
Conclusion

1. **Stressor Identification**

   1. **Voltage:**
      1. Cumulative Thermal Cycling

   2. **Current:**
      1. Cumulative Temperature

2. **Improved Modeling**

   1. Improved accuracy
   2. Better than standard assumption (0.5%/year)
Future Work: Degradation Models Based on Indoor Tests

1. Estimate Overall Exposure
   a. Indoor - IEC 61215
   b. Outdoor – Weather measurements

2. Performance
   1. Measure Series Resistance from I-V Curves

3. Evaluate
   1. Relationship between change in $R_s$ and Cumulative Temp. Cycling

Thermal Cycling Exposure

Estimated exposure to thermal cycling

![Graph showing estimated thermal cycling exposure over time]

R$_s$ vs Thermal Cycling

- Linear Fit ($R^2 = 0.97$)
- Initial
- TC200
- TC500
- Outdoor Actual

![Graph showing correlation between series resistance and cumulative thermal cycling factor]
Questions
References


