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Moisture Ingress Models of Film Capacitors in PV Inverters

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Background

- Funding provided by U.S. Department of Energy Solar Energy Technologies Office

- Project title: “Power Electronics Reliability Standards”

- Team members:
  - Jack Flicker, Principal Investigator Sandia National Laboratories
  - Peter Hacke, Michael Kempe, MCCS National Renewable Energy Laboratory

- Outcomes:
  - Led to publishing of second version of IEC 62093 (IEC 2022)
  - Effects of advanced inverter functionalities on photovoltaic (PV) inverter reliability (Flicker et al. 2022).

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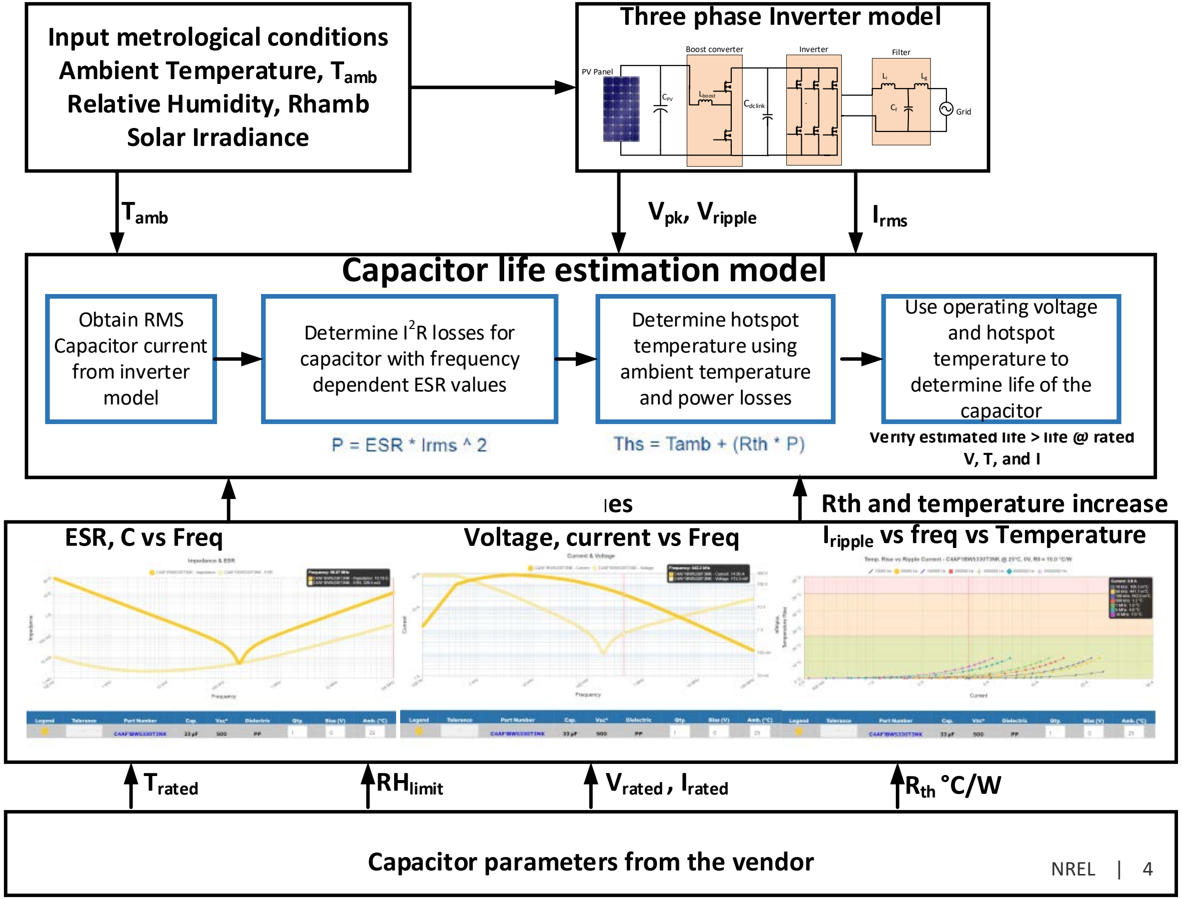
Electrothermal Models

- Power loss in a capacitor translates to temperature increase.
- The internal series resistance, ESR, and thermal resistance, R_{th}, are easily available.
- A temperature increase at each time step can be translated into damage accumulation of the capacitor.
- Lifetime models and degradation models are available,



Humidity Models

- Thermal models for inverter units, with consideration for humidity
- Humidity introduces corrosion and other failure mechanisms, such as ion migration, diffusion, and condensation in a PCE.
- Humidity affects various components within a PCE (Hacke et al. 2018):
  - Capacitors (Brown et al. 2022)
  - Film resistors
  - Insulation resistance reduction
  - Integrated chips.

Component	Type	Failure Modes	Failure Mechanisms	Critical Stressors	O	S	D
Capacitor	Film (Used for DC Link and AC Filter)	Capacitance Drop	High temperature will degrade the polymer dielectric	T_A	8	7	2
			Corrosion of metallization can lead to reduction in effective conductor area	RH, V	8	7	2
			Self heating due to overcurrent or overvoltage	V_C, I_C	8	7	2
			Corona effect: decrease in dielectric strength of the gas between dielectric films resulting from insufficient space factor control during design	RH, T_A	8	8	3

Lifetime Estimation of Capacitors—Equations

- Capacitor sensitivity to temperature, relative humidity (RH), applied voltage, and ripple current (Gallay 2016)

$$L_{n1} = L_R \times 2^{\left(\frac{T_R - T_{c2}}{10}\right)}$$

L_{n1} – Expected life at rated voltage at operating temperature

L_R – Estimated life at rated temperature

T_r – Rated temperature

T_{c2} – Measured temperature

$$L = L_{n1} \times \left(\frac{V_r}{V_o}\right)^n$$

L_{n1} – Expected life at rated voltage

L – Estimated life at operating voltage

V_r – Rated voltage

V – Operating voltage

n – Voltage coefficient

$$t(RH) = t_{H_n} \left(\frac{RH_n}{RH}\right)^m$$

T(RH) – Expected life at operating RH conditions

t_{Hn} – Estimated life at rated RH

RH_n – Rated RH

RH – Operating RH

m – Humidity coefficient

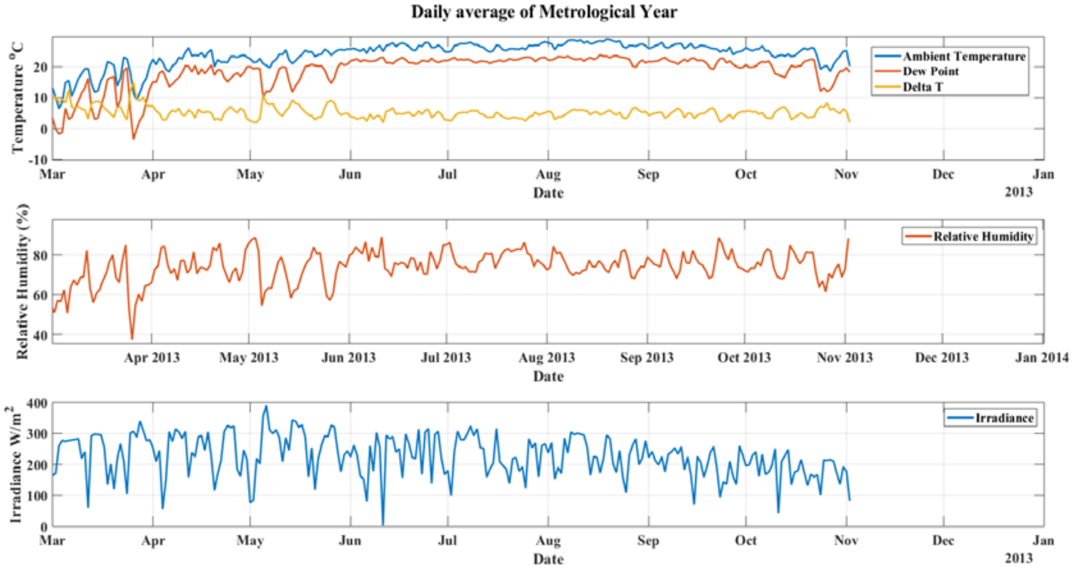
$$t(T, U, RH) = t_{T_n, U_n, RH_n} \exp\left(\frac{E_a}{k_B}\left(\frac{1}{T} - \frac{1}{T_n}\right)\right)\left(\frac{U}{U_n}\right)^{-n}\left(\frac{RH_n}{RH}\right)^m$$

Motivation

- Current life estimation and acceleration models for humidity use a single data point for maximum voltage, temperature, and relative humidity.
- This method can be used for profiles with fixed operating conditions. This is sufficient for design qualification tests.
- Mission profile varies throughout the operating life of a PV inverter.
- It is necessary to measure damage accumulation through a time series-based analyses for changing operating conditions of voltage, temperature, and relative humidity.

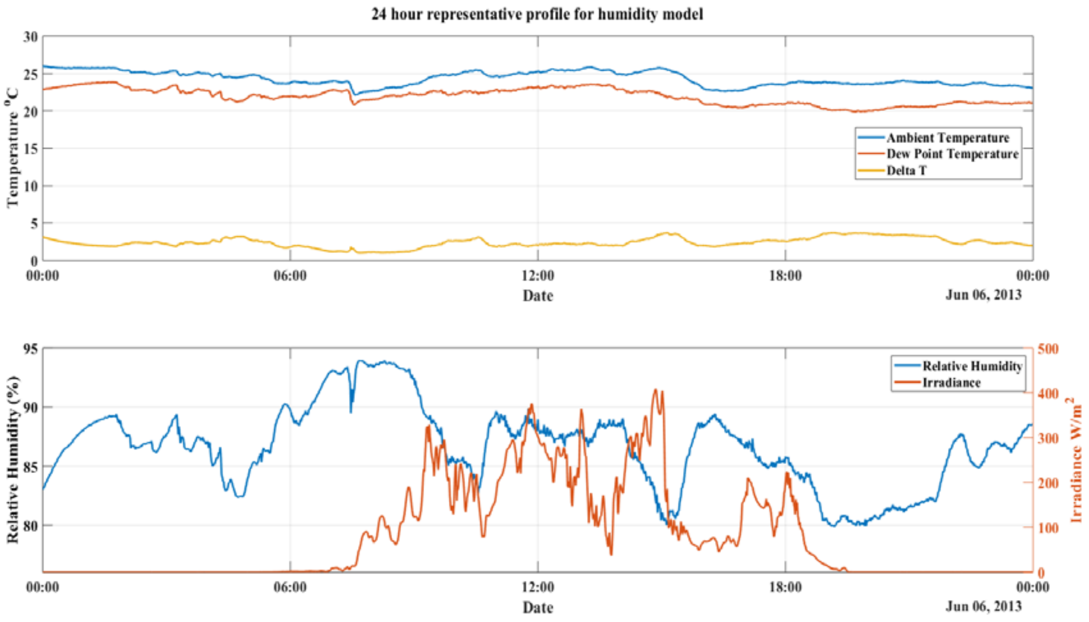
Twenty-Four-Hour Profile Development

- To test the inverter for validation of the humidity model, a representative profile consisting of ambient temperature, relative humidity, and irradiance profile needs to be provided as input to the thermal chamber with the PCE under test.
- Metrological year data of Miami consisting of 8 months of ambient temperature, dew-point temperature, relative humidity, and global horizontal irradiance were sampled at a rate of 0.05 Hz/1 sample per 20 seconds.
- Twenty-four-hour rainy warm conditions with low irradiance was selected:
    - Hot and humid conditions, which leads to condensation
    - Low irradiance conditions were chosen because high irradiance leads to greater output power heating up the PCE, driving away the moisture.



Twenty-Four-Hour Profile Development

- Ten days of interest are chosen to narrow down the data set.
  - For each day, the maximum and minimum relative humidity are obtained and used to compute the difference in relative humidity (Thiagarajan, Hacke, and Flicker 2021).
  - The days with the lowest difference in relative humidity are further selected.
- From the days with the lowest difference in relative humidity, the maximum irradiance of the days is listed.
- Then, the days with the lowest maximum irradiance are chosen.



Capacitor Temperature and Surface Relative Humidity

- Capacitor surface relative humidity is determined using the capacitor surface temperature, based on dew point (TD) and relative humidity (RH).

$$TD = 243.04 * \frac{\ln\left(\frac{RH}{100}\right) + \left(\frac{17.625 * T}{243.04 + T}\right)}{17.625 - \ln\left(\frac{RH}{100}\right) - \left(\frac{17.625 * T}{243.04 + T}\right)}$$

$$RH = 100 * \frac{exp\left(\frac{17.625 * TD}{243.04 + TD}\right)}{exp\left(\frac{17.625 * T}{243.04 + T}\right)}$$

Test Details	Power (W)	Chamber T	Chamber RH	Capacitor Temperature	Capacitor Surface RH
00:00 – 02:00	0	25.9 °C	85%	28.7 °C	72%
02:00 – 04:00	0	25.3 °C	88%	28.1 °C	75%
04:00 – 06:00	0	24.9 °C	86%	27.7 °C	73%
06:00 – 08:00	0	23.8 °C	91%	26.6 °C	77%
08:00 – 10:00	400	23.2 °C	93%	26.1 °C	78%
10:00 – 12:00	800	24.7 °C	88%	27.8 °C	73%
12:00 – 14:00	1100	25.4 °C	88%	28.5 °C	73%
14:00 – 16:00	1200	25.3 °C	85%	28.3 °C	71%
16:00 – 18:00	450	22.9 °C	88%	25.9 °C	73%
18:00 – 20:00	400	23.7 °C	83%	26.7 °C	69%
20:00 – 22:00	0	23.8 °C	81%	26.7 °C	68%
22:00 – 24:00	0	23.5 °C	87%	26.3 °C	74%

Prior Work—Moisture Ingress Rates for PV Panels

- Time series-based estimate for moisture ingress into PV panel for lifetime determination (Kempe 2006)

- Parameters:
    - Ambient temperature
    - Voltage
    - Relative humidity.

- Material parameters:
    - Activation energy for diffusivity
    - Activation energy for solubility
    - Thermal equilibrium time
    - Moisture equilibrium time.

Modeling of rates of moisture ingress into photovoltaic modules

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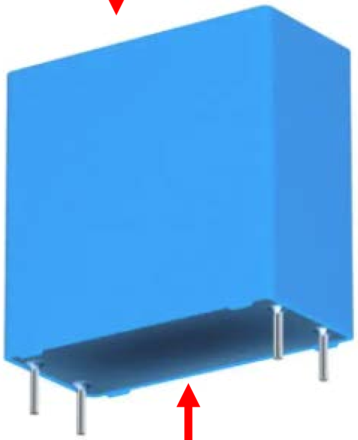
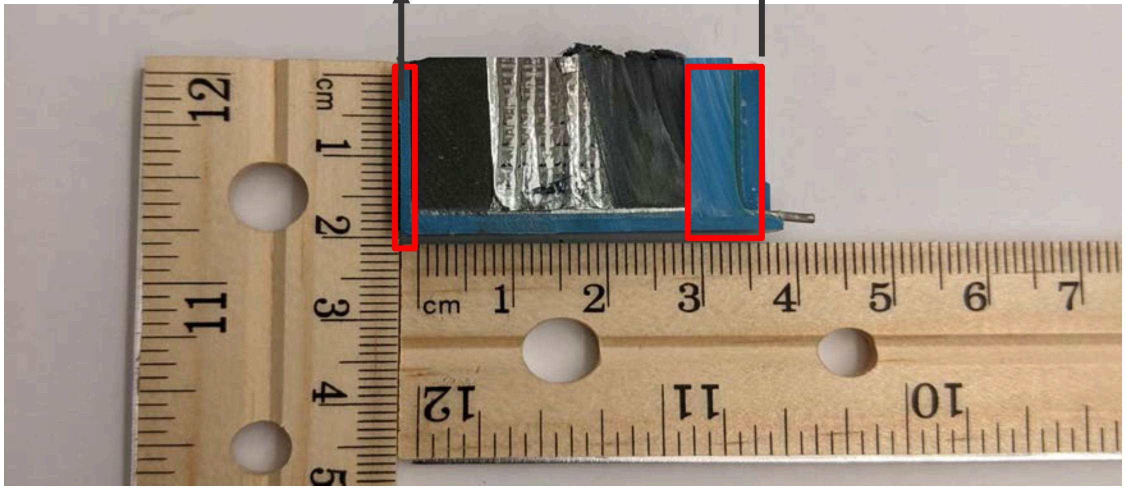
FTIR Analysis

- Capacitor samples were desoldered from the inverter device under test.
- Capacitors were mechanically sawed off and visually examined to understand fastest path for moisture ingress to cause capacitor failure.
- Fourier transform infrared spectroscopy (FTIR) analysis was performed on highlighted layers to understand material composition.





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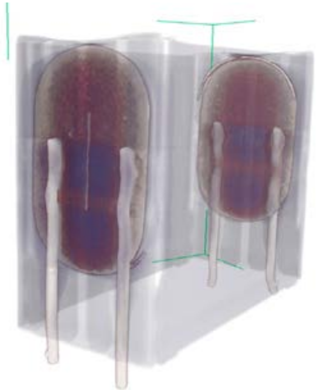
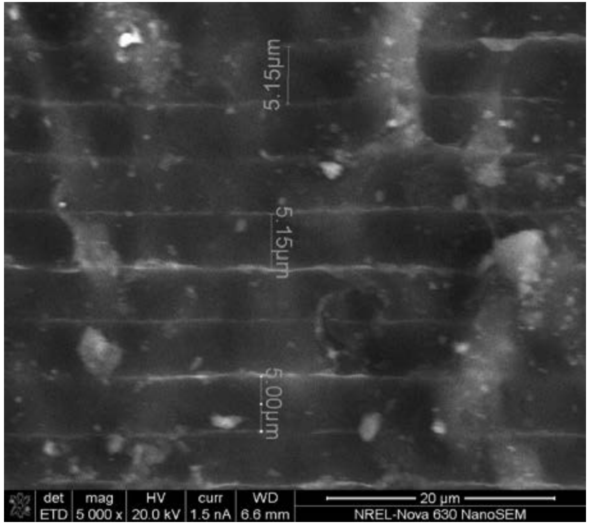
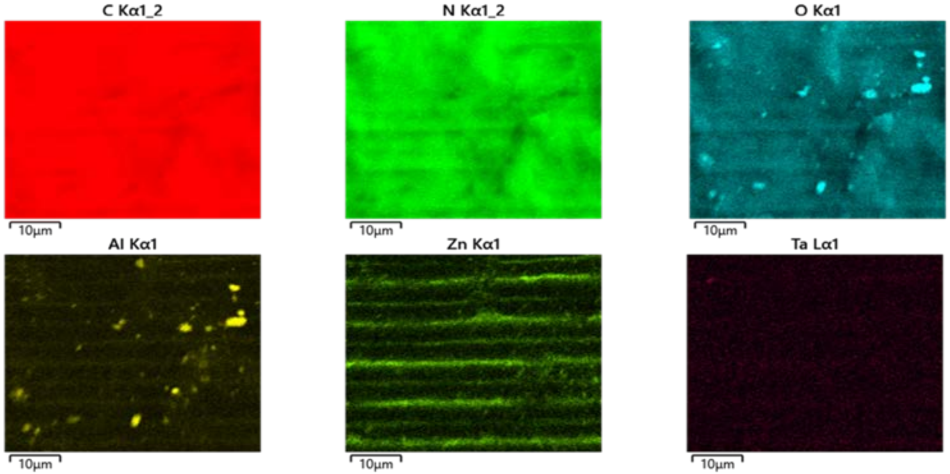
FTIR and X-Ray Tomography Analysis

- Moisture ingress calculation—required parameters:
  - Material composition -> Activation energy and diffusion coefficients
  - Dimension measurements.
- Estimate time to failure of the device based on moisture permeation.
- X-ray tomography of capacitor was performed to understand the geometry of the film capacitor.
- This was performed to understand the possible path for moisture ingress.







Metal used for the capacitor is Zn, the layer thickness is 4-5 µm

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Experimental Parameter Assumptions

- Assume:
  - Humidity equilibration time is 500 hours.
    - Activation energy for diffusivity of 46 kJ/mol
    - Activation energy for solubility of 17 kJ/mol.
  - Thermal equilibration time is 30 minutes.
    - Assume the capacitor will be 5°C above ambient when the irradiance is 1000 W/m^2.
    - Use irradiance from a single-axis tracking system.
  - For voltage, we assumed that the converter voltage is at the maximum operating value whenever the sun is above 25 W/m^2 and degradation only occurs above this irradiance value at the modeled test conditions.

Experimental Setup—Moisture Ingress Estimation

- The capacitor samples were cycled at 25°C 5% relative humidity and 85% relative humidity. Then, they were repeated at 85°C 5% relative humidity and 85% relative humidity.
- Capacitance and ESR were measured and recorded every 10 minutes.

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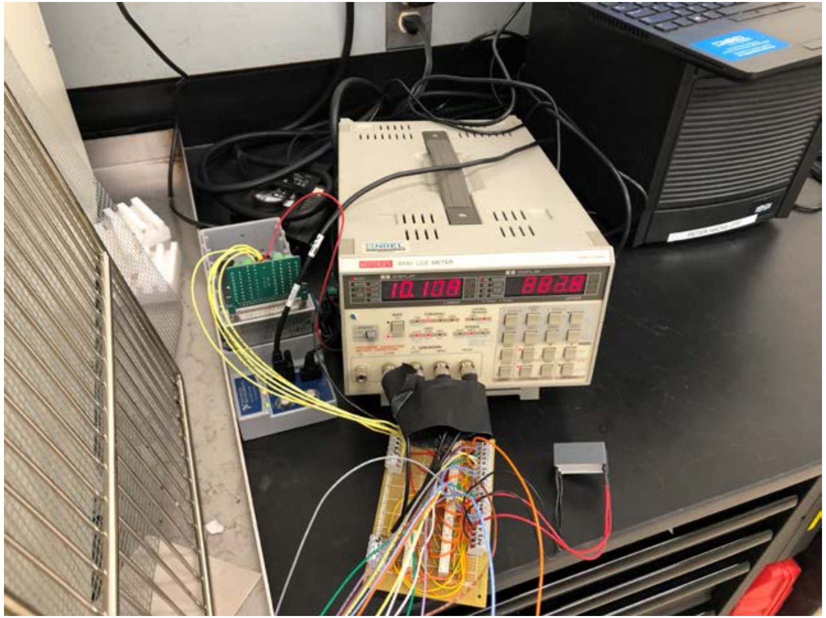
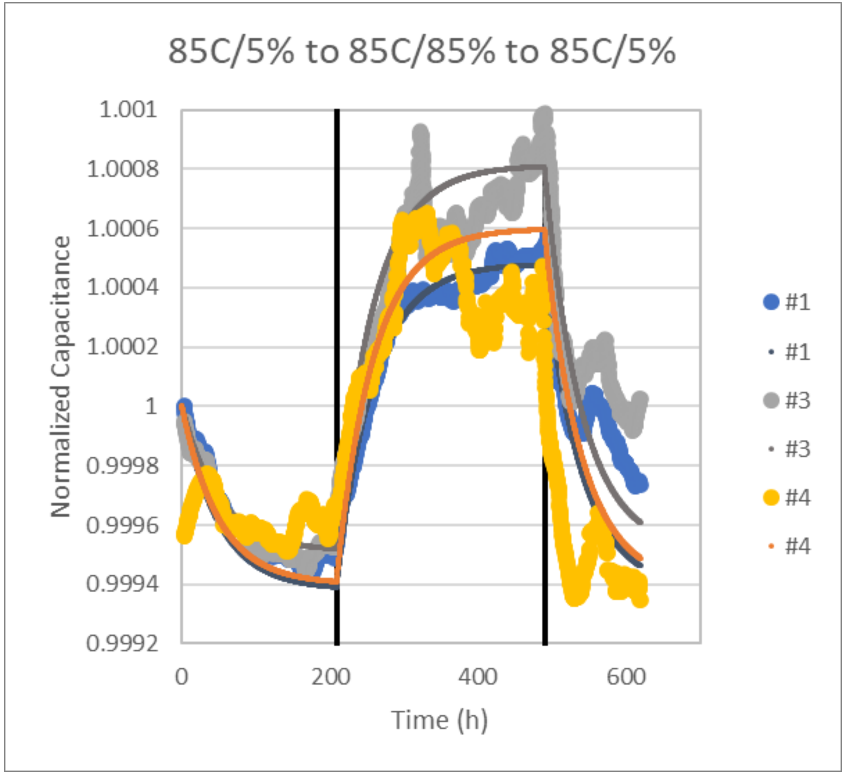


Moisture Ingress at 85°C

- This experiment was started immediately after the experiment at 25°C/85% relative humidity with the temperature at 85°C and the relative humidity going from 5% to 85% and back to 5%, switching at 209 hours and 490 hours.
- The response to the step changes was modeled with a 50-hour characteristic decay constant.
- This provides a new and unique method for determining the moisture ingress rates for capacitors.



$$\frac{dC}{dt} = -\frac{C - C_{eq}}{\tau}$$

Conclusion and Other Contributions

- A twenty-four-hour-long profile was identified from a high-resolution field data set consisting of eight months of metrology and irradiance measurements.
- A first principles-based approach to identify the moisture ingress into a capacitor was developed.
- The material composition obtained from FTIR was used to create detailed diffusion models of the capacitor.
- Experiments were performed for to determine the moisture ingress time, which is the first of its kind, to estimate moisture ingress in and out of the capacitor device under normal and extreme temperatures and relative humidity conditions.
- A methodology was developed to model humidity effects for any electronic component.

References

Brown, Buck, Zheyu Zhang, Johan Enslin, Shuangshuang Jin, Ramtin Hadidi, Jin Tan, Peter Hacke, Ramanathan Thiagarajan, Shuan Dong, Xiaonan Lu, Miles Russell, Matt Ursino, Joe Hodges, Brendan Ford, and Daniel Clemens. 2022. "Failure Mode and Effects Analysis for a Photovoltaic Inverter." Presented at the 2022 Photovoltaic Reliability Workshop.

Flicker, Jack, Jay Johnson, Peter Hacke, and Ramanathan Thiagarajan. 2022. "Automating Component-Level Stress Measurements for Inverter Reliability Estimation." *Energies* 15 (13): 4828.

Gallay, Roland. 2016. "Metallized Film Capacitor Lifetime Evaluation and Failure Mode Analysis." *arXiv preprint arXiv:1607.01540*.

Hacke, Peter, Sumanth Lokanath, Paul Williams, Arvind Vasan, Paul Sochor, GovindaSamy TamizhMani, Hirofumi Shinohara, and Sarah Kurtz. 2018. "A Status Review of Photovoltaic Power Conversion Equipment Reliability, Safety, and Quality Assurance Protocols." *Renewable and Sustainable Energy Reviews* 82: 1097–1112.

International Electrotechnical Commission (IEC). 2022. IEC 62093:2022 – Photovoltaic system power conversion equipment – Design qualification and type approval.

Kempe, Michael D. 2006. "Modeling of Rates of Moisture Ingress Into Photovoltaic Modules." *Solar Energy Materials and Solar Cells* 90 (16): 2720–2738.

Thiagarajan, Ramanathan, Peter Hacke, and Jack Flicker. 2021. "Development of Mission Profiles for Humidity Models in the Reliability Testing of PV Inverters." Presented at the 38th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2021), September 6–10, 2021. NREL/CP-5D00-80375.

Thank you

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