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DEVELOPMENT OF MISSION PROFILES FOR HUMIDITY MODELS IN THE RELIABILITY TESTING OF PV INVERTERS

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ABSTRACT: To understand the impacts of humidity on photovoltaic (PV) inverters, mission profiles were developed to accurately describe the different processes and rates based on the environmental factors of temperature, relative humidity, and irradiance. The operating environment of the device introduces stress factors dependent on component temperature, relative humidity, and component voltage. The development of profiles started from looking at historical climate conditions at Cocoa, Florida, a hot and humid location. The profile developed from the field location was compared with existing humidity test profiles in industrial and military standards to determine acceleration factors. Prior to the evaluation of the mission profiles, critical components in the PV inverter were identified based on vendor discussions along with failure modes of interest. The profiles considered in this study were demonstrated using a 4-kVA string inverter. The measurements from the critical components including film capacitor were substituted in the device manufacturer-specified equation to determine the severity of each test. The severity of each test was compared against the severity of the 24-hour result to determine the acceleration factor of each test. The acceleration factors were determined to be within a range of 1.2-6 for the existing humidity tests from standards when compared against the mission profile developed from field data. This optimal humidity/thermal profile will be passed to the International Electrotechnical Commission (IEC) standards development group for inverter qualification testing.

Keywords: Inverter, Reliability, Qualification and Testing, and System Performance.

1 INTRODUCTION

Photovoltaic (PV) inverters installed in the field are subjected to multiple stresses throughout their life. Among the various stresses, temperature and relative humidity play a very important role during the life of the PV inverter. High ambient temperature in addition to the temperature increase contributed by powering of the device causes degradation to temperature-sensitive devices, such as electrolytic capacitors used in DC-link applications and transistor modules [1]. The effects of temperature can be easily visualized through a physics-based electrothermal model [2]. On the other hand, humidity produces long term effects on the electronic components inside the inverter. Humidity leads to corrosion, which is accelerated by residual halogens in various devices. Humidity diffuses through potting or conformal coatings of the inverter, and under condensing conditions, it precipitates, causing corrosion. Powering the inverter simultaneously drives out humidity, but it also drives failures associated with ion migration.

The current testing methods for electronic components including capacitors involves accelerated testing using constant temperature, relative humidity, and voltage bias. The Hallberg-Peck paper [3] provides acceleration factors for total time in testing and it treats the effect of moisture ingress into the plastics. In [4], the remaining lifetime estimate of the metallized capacitor was estimated against standard operating conditions accounting for temperature variation, relative humidity variation, and voltage variation. Capacitor manufacturers also use the temperature–humidity–bias test to calculate acceleration factors for capacitors operating under high temperature and high humidity variation [5]. The design qualification testing for the capacitors is performed at a uniform temperature, voltage, and humidity setpoint throughout the test duration. In the field operation of a PV inverter throughout 24 hours of the day, the inverter, and the critical components inside the inverter, including the film capacitors, are subjected to varying irradiances that drive inverter power, varying temperature, and varying humidity which can introduce different failure mechanisms due to these transient processes compared to standard qualification testing.

To understand these transient processes, a representative 24-hour profile was chosen from the field data of a hot and humid location in Florida. Section II deals with the development of the mission profiles. Section III discusses the validation of the profiles along with the selection of the critical inverter components sensitive to humidity effects. Section IV covers the results of the tests along with the acceleration factors. Section V discusses the conclusions from the tests.

2 DEVELOPMENT OF MISSION PROFILES

Metrological year data of Cocoa, Florida, a location known for its humidity, was chosen for the representative profile. The data consisted of 8 months of ambient temperature, dew point temperature, relative humidity, and global horizontal irradiance sampled at a rate of 0.05 Hz / 1 sample per 20 seconds.

For the representative model for humidity, a day with warm rainy conditions coupled with low irradiance data was chosen. Warm, rainy conditions were chosen to replicate the hot and humid conditions that lead to condensation, and low-irradiance conditions were chosen because high irradiance leads to greater output power heating up the power conversion equipment and driving away the moisture.

The high-resolution metrological data were narrowed down to the day (24-hour profile) with warm, rainy conditions with low irradiance using the following methodology:

1. A daily average of the metrological data was created. Along with the raw data, a difference in ambient temperature and dew point temperature was included in the daily average data. These data were plotted against time to select the days of interest. The days of interest included the days with least difference of ambient and dew point temperature, implying very high relative humidity, and low irradiance. Figure 1 shows the daily average of the metrological year with separate subplots for temperature, relative humidity, and solar irradiance.

2. From Figure 1, using visual inspection, 10 days of interest were chosen to narrow down the dataset. For each of these days, the maximum and minimum relative humidity was obtained and used to compute the difference in relative humidity. The days with lowest difference in relative humidity were further selected.

3. From the days with the lowest difference in relative humidity, the maximum irradiance of the days was listed. Then, the day with lowest maximum irradiance was chosen.

4. In summary, the day with a combination of the lowest difference in relative humidity and the lowest maximum irradiance was chosen as the representative 24-hour profile for the PCE device under test. Figure 2 shows the 24-hour representative profile selected from the high-resolution metrological data.

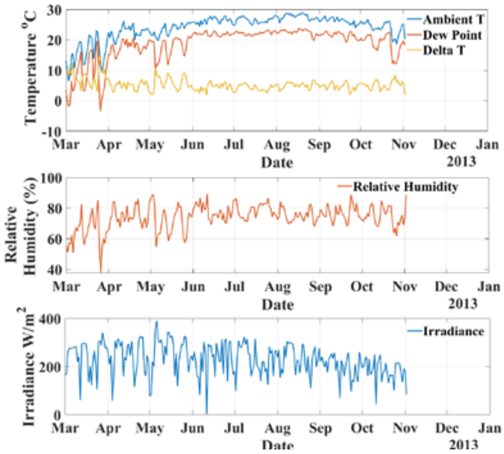

Fig. 1: Daily average of metrological year of Cocoa

This mission profile presents conditions where the inverter experiences high-humidity, zero-power conditions in the initial hours of the profile, leading to condensation. Then, as the temperature increases through powering of the profile, it leads to further retention of moisture. At the end of the profile, the temperature decreases as the device is powered off. These temperature and humidity conditions coupled with low irradiance throughout the day makes this profile a good candidate for testing humid conditions.

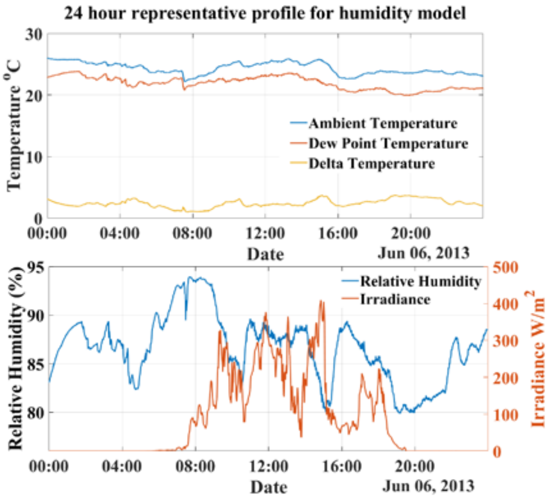

Fig. 2: 24-hour representative profile for humidity model

To demonstrate the mission profile, a U.S. market, 120/240-V, split-phase, 4-kVA string inverter with two independent DC maximum power point tracker inputs for differing PV module strings was characterized and tested. DC power was supplied to the inputs with Keysight N8937APV solar array simulators. The power at the inverter inputs and output was monitored with Yokogawa WT 330 power analyzers. A diagram of the apparatus is shown in Figure 3.

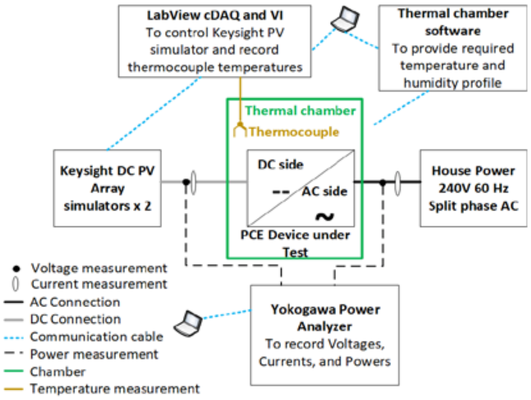

Fig. 3: Experimental setup for validation of humidity mission profile

The critical components of the inverter were identified based on the status review of the PV equipment reliability [6], the PVQAT Failure Modes and Effects Analysis sheet [7] on inverters, and on further discussion with vendors. Based on these discussions, the components under interest were narrowed down to film capacitors, solid-state relays, and electrolytic caps. With this assumption, thermocouples were placed on these components to measure the temperature and to calculate the relative humidity on their surfaces.

Considering the time, it takes to soak the chamber to the given relative humidity setpoint, and with very little variation of temperature throughout the given day, the 1-minute, 24-hour profile for the given day was reduced to a 2-hour step, 24-hour profile, as shown in Figure 3. The experiment was performed inside the chamber with a tolerance of ±1°C and ±3% relative humidity.

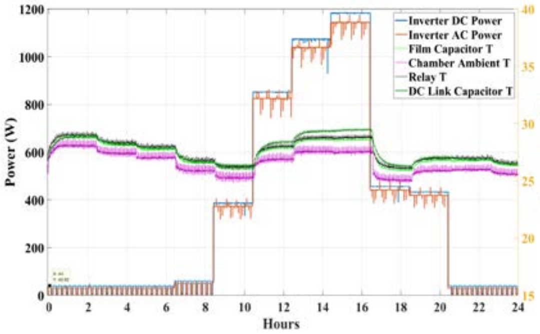

Fig. 4: DC and AC power measurements - 24-hour rainy-day profile

The power and temperature values measured from this experiment were used as input, along with the relative humidity data, to determine the severity of the humidity test. The ambient temperature, T, and relative humidity, RH were used to determine the dew point temperature, TD, of the setup [14]. The dew point temperature and measured capacitor temperature were used to determine the relative humidity on the capacitor surface. The dew point and ambient temperature are expressed in °C, and relative humidity is expressed in percentage, %.

$$TD = 243.04 * \frac{\ln\left(\frac{RH}{100}\right) + \left(\frac{17.625 * T}{243.04 + T}\right)}{17.625 - \ln\left(\frac{RH}{100}\right) - \left(\frac{17.625 * T}{243.04 + T}\right)} \qquad (1)$$

$$RH = 100 * \frac{exp\left(\frac{17.625 * TD}{243.04 + TD}\right)}{exp\left(\frac{17.625 * T}{243.04 + T}\right)} \qquad (2)$$

Based on this formulae, the calculations were repeated for 40°C and 93% RH damp heat test, as recommended in method 103B of MIL-STD-202G, shown in Figure 5. With ambient conditions of 40°C and 93% RH, the dew point temperature, TD, is estimated to be 38.65°C. Based on the dew point temperature, TD, and the capacitor temperature of 42.2°C, the relative humidity on the surface of the capacitor is estimated to be 83.19%, shown in Figure 5.

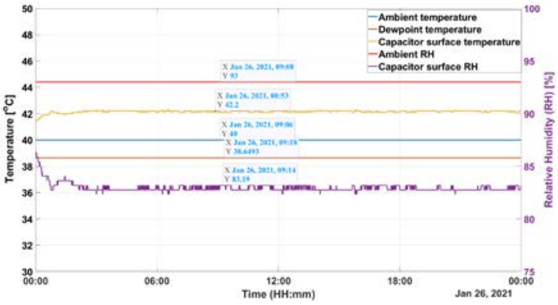

Fig. 5: Temperature and relative humidity data from MIL-STD-202G standard method 103B

The same procedures were repeated for MIL-STD-750D (moisture resistance test at 10% of rated power) and MIL-STD-810G (natural cycle humidity test at 10% of rated power). The capacitor temperatures measured from the experiments are plotted in Figure 6.

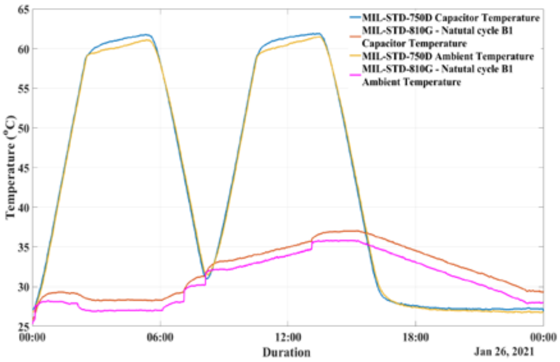

Fig. 6: Capacitor temperature measurements from standard tests

The severity of any humidity test is estimated based on the manufacturer-specified equation for humidity testing [9]. The manufacturer-specified equation is based on the severity test mentioned in the International Electrotechnical Commission (IEC) 60068-2-78 [8].

The severity, S, of any humidity test can be defined as the product of two factors:

$$S = \rho \times F_D \qquad (3)$$

Where ρ is the density of water vapor in air, which is a function of both relative humidity and temperature, expressed in g/m^3. Psychrometric charts were used to evaluate the density of water vapor in air when the temperature and relative humidity are known.

F_D is the thermal acceleration factor for diffusion.

$$F_D = \exp\left(\frac{-E}{RT}\right) \qquad (4)$$

In this equation, E is the activation energy for diffusion (1.0E4 cal/mol), R is the universal molar constant for gases = 1.987 cal/mol K, and T is the Temperature in kelvins = T (in °C) + 273.

4 RESULTS

The 24-hour experiments performed for the representative rainy day in Florida were completed, along with the humidity tests from the industrial and military standards mentioned, in addition to recording of AC and DC power data along with temperature measurements. The measurements from this test were substituted in the manufacturer-specified equation to determine the severity of the test condition and compare it to the baseline data of the Florida rainy-day profile, as shown in Table 1.

Table I: Severity and acceleration factors for the humidity profiles under consideration

Name of the profile	Severity	Acceleration factor
Florida 24-hour rainy-day profile	6.98E-05 (Baseline)	1
MIL-STD-202G (40°C 90% RH steady-state at 10% of rated power)	0.000129	1.84
MIL-STD-750D (moisture resistance test at 10% of rated power)	0.000135	1.9326
60°C 85% RH (modified IEC 62093 Damp heat test at 10% of rated power)	0.000474	6.756
MIL-STD-810G (natural cycle humidity test at 10% of rated power)	7.81E-05	1.118

Severity at Florida 24 hour profile, $S = \Sigma\ (\rho \times F_D) = 6.98 \times 10^{-5}$

Severity at 40°C 93% RH (MIL-STD-202G), $S = \Sigma\ (\rho \times F_D) = 1.088 \times 1.181 \times 10^{-5} = 0.000129$

Comparing the MIL-STD-202G humidity test with that of the Florida rainy-day profile showed a severity ratio of 1.8, implying that the MIL-STD-202G humidity test stresses the device 1.8 times faster than the baseline calculation.

5 CONCLUSION

The mission profiles for the humidity modeling were developed using field data from Florida based on the conditions of a warm, rainy day with low irradiance. This profile was compared against the humidity test profiles from existing industrial and military standards for testing the humidity of the electronic components. These tests were validated using a 4-kVA inverter inside a thermal chamber. The severity of the tests was estimated using the manufacturer-specified equations, and acceleration factors were determined.

6 ACKNOWLEDGEMENTS

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