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Reliability Study of Electrolytic Capacitors in a Micro-Inverter

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1   Abstract

This paper provides a systematic method for estimating the useful life of electrolytic capacitors used in the Enphase Energy micro-inverters designed for photovoltaic (PV) systems. The findings confirm that with a conservative model the useful life of these capacitors exceeds 50 years.

2   Premise

Micro-inverters have emerged as a new class of photovoltaic inverters in grid-tied applications. They provide increased energy harvest, improved system availability, and simplified design and installation of solar system compared to traditional inverters. However, for micro-inverters to succeed in practical applications and be accepted by the marketplace, the reliability of micro-inverters must demonstrably exceed that of traditional string inverters.

Common causes for failures in power converters of all kinds include the lack of sufficient design margin in component ratings, the inability to survive abnormal operation, manufacturing defects or poor quality control, random failures, and general part wear and tear. Electrolytic capacitors are a common point of failure or reliability problems in power electronics. This paper will explain the deterioration of electrolytic capacitors in micro-inverters and show, using conservative testing criteria, how the electrolytic capacitors as deployed in Enphase Energy Micro-inverters "live" longer and thereby do not degrade the reliability of the entire photovoltaic power system.

3   Need for capacitors

Inverters convert the DC power produced by a power source to AC power for use in homes and businesses. Photovoltaic modules are the DC power source used in solar power systems. The equations below explain how photovoltaic power is measured.
The input power equation is given by:

$$P_{pv} = V_{pv} * I_{pv}$$

Where P_{pv} is the PV power in W, V_{pv} is the PV voltage in V and I_{pv} is the PV current in A.

The output power equation is given by:

$$P_{ac}(t) = P_{avg}*(1\text{-}\cos(2\ \omega\ t))$$

Where ω is the grid angular frequency and P_{avg} is the average output power.

The inverter must produce $P_{ac}(t)$ while receiving P_{pv} on its input. This results in a large ripple on the output power. Ideally, P_{avg} equals P_{pv}, which means that energy has to be stored and retrieved in the inverter.

A capacitor is commonly used to store the energy that must be stored and retrieved by the inverter. This capacitor is usually located on the PV bus, and has to be large enough to control the voltage ripple across the bus. This ripple would be detrimental to MPPT accuracy otherwise.

Electrolytic capacitors are very well suited to control the ripple because of their low Equivalent Series Resistance (ESR) and high capacitance per volume.

4   Electrolytic capacitor technology

4.1 Useful Life

The useful life of capacitors is reported in number of hours of operation at a given temperature, operating voltage and ripple current. For traditional power converters, an acceptable useful life of capacitors is as low as 2000h at 85°C.

Out of desire to increase the reliability of its inverters, Enphase Micro-inverters use capacitors rated from 4000 to 10000h at 105°C. The capacitor lifetime is very sensitive to temperature as its useful life doubles for every 10°C temperature drop.

4.2 End of life

When the capacitors are close to their end of life, their capacitance decreases and their ESR increases. The elevated ESR creates more power dissipation in the capacitor which elevates the internal temperature, thereby accelerating the aging process.
Capacitors are usually rated for a given number of hours at a given operating temperature, voltage and ripple current.
When operating in those conditions, the capacitors are not to exceed their end of life criteria, which are typically a 20% drop in value and a doubling of the ESR.

4.3 Recommendation

For a list of excellent papers on electrolytic capacitors, please consult Appendix A.

5   Lifetime Evaluation

5.1 Environment

A micro-inverter is typically mounted on the rack which supports the PV modules. Its ambient temperature is higher than the open air temperature because of the sun power being dissipated by the PV modules. Its internal temperature is higher than ambient because of internal power dissipation due to power conversion.
A field proven temperature rise model for a typical Enphase Energy product is:

$$\Delta T = P_{ac}*0.15$$

With P_{ac} in W and ΔT in °C.

The coefficient in this equation is affected by the conversion efficiency of the micro-inverter, thermal management of the unit, and by the unique conditions of an actual installation. The coefficient used in this equation is conservative.

The Ripple current in the capacitor is derived by:

$$I_{cap} = P_{pv} / V_{pv} * \sqrt{2}$$

Where I_{cap} is the RMS capacitor ripple current in A, P_{pv} is the PV Power in W, and V_{pv} the PV voltage in V.

Note that this equation is valid because there is no significant power conversion induced high frequency ripple current in the electrolytic capacitors.

5.2 Climatic impact

On one hand, a high open air ambient temperature raises internal inverter temperature, but on the other hand, the PV module efficiency drops when the PV cell temperature increases. The present study used actual irradiance and ambient data to estimate real life condition in the capacitor such as voltage, ripple current and temperature.

5.3 Impact of a failed capacitor on the micro-inverter

Because several electrolytic capacitors are paralleled in the micro-inverter, and because capacitors normally fail open, there is in fact very little impact on the micro-inverter if a capacitor fails. The main impact is that MPPT efficiency is slightly reduced because there is now more ripple voltage on the PV bus.

5.4 Climatic data

The climatic and irradiance data used in this test was obtained from the National Solar Radiation Data Base (NREL), which provides hourly meteorological data for locations throughout the United States.
http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Palm Springs, CA was chosen as the location for this study due to the high average temperatures and irradiance numbers, to ensure that the test is performed under challenging conditions.

5.5 Photovoltaic module characteristics

This study uses a typical 205W STC, 72 cell module with a V_{mp} of 35V at 25°C.
The STC power is measured at cell temperature of 25°C and an irradiance of 1000W/ m^2.
The power temperature coefficient used is β=0.0048/°C, per typical vendor information.

The cell temperature rise coefficient is δ=0.04°C/W/m^2.
The cell temperature T_c is computed from the ambient temperature T_a and the irradiance I_r as:

$$T_c = T_a + δ * I_r \tag{1}$$

The PV power is found as:
$$P_{pv} = P_{stc}*(Ir/1000)*(1- β*(T_c -25)) \tag{2}$$

Vmp is found to be affected by temperature and by a temperature coefficient, typically λ=0.0034/°C.
Therefore the PV voltage V_{pv} is found to be:
$$V_{pv} = V_{mp}*(1- λ*(T_c-25)) \tag{3}$$

5.6 Inverter power

The inverter power is:

$$P_{ac} = P_{pv}*\eta \qquad\qquad (4)$$

Where η is the efficiency of the unit, in this case 95%.

5.7 Ripple current

The ripple current in a single capacitor is computed as:

$$I_{cap} = P_{pv} / V_{pv} * \sqrt{2} * n \qquad\qquad (5)$$

With n being the number of paralleled capacitors.

5.8 Lifetime index

A lifetime hourly index ε is computed. This index measures the portion of the capacitor lifetime that has been used. The hourly index is computed as:

$$\varepsilon = 1/\left[Lu * 2^{\left[(T0 - T)/10\right]} \right] \qquad\qquad (6)$$

Where L_u is the useful lifetime rating, T0 is the temperature for that rating, and T is the actual capacitor temperature.

The capacitor lifetime budget will have been spent when:

$$\Sigma\varepsilon = 1$$

For instance, for a capacitor rated at 10,000h at 105°C, after 1h at 65°C, ε=6.25E-6, which means that it could survive 160,000h at this temperature. This is consistent with the Arrhenius law equations used by all commercial capacitor vendors.

5.9 Yearly data

To simulate performance over an entire year, P_{pv}, V_{pv}, I_{cap} and ε are computed each hour using equations (1) – (6) based on the Palm Springs location, and using the PV module defined above and 4 capacitors rated at 4000h at 105°C.

The following extrema are recorded over the course of a year:

	T_{amb} (°C)	P_{pv} (W)	P_{ac} (W)	T_{cap} (°C)	V_{pv} (V)	I_{cap} (Arms)	ε
Minimum	4	0	0	4	0	0	2.28E-7
Maximum	46	166.71	158.38	64.91	37.08	0.99	1.55E-5

ε is accumulated for the entire year and the result is:

$$\Sigma\varepsilon = 2.02e^{-2}$$

The results show that for each year only 2% of the capacitor's useful life is used.
This means that the expected useful lifetime of the capacitors is **50 years**.

This number is considered conservative because the useful life given by the vendor is for a specified ripple current, which is approximately 3 times higher than the maximum current seen by the part used in this test.

Additionally, the voltage applied to the capacitor is close to half of the rated voltage. According to some vendors, this condition significantly improves the actual useful life of the

part by a conservative 2x factor, increasing the expected lifetime of the capacitor to approximately **100 years.**

6   Conclusion

This study has shown that electrolytic capacitors are not a significant point of failure for micro-inverter reliability. The useful life is estimated to be well in excess of 50 years even when the inverter is located in a harsh environment.

7   Acronyms

AC   Alternative Current
AVG   Average
DC   Direct Current
ESR   Equivalent Series Resistance
MPPT   Maximum Power Point Tracking
PV   Photo-Voltaic
STC   Standard Test Conditions

Appendix A

References:

General Descriptions of Aluminum Electrolytic Capacitors –
http://nichicon-us.com/english/products/pdf/aluminum.pdf

Reliability of CDE Aluminum Electrolytic Capacitors –
http://www.cde.com/tech/reliability.pdf

Deriving Life Multipliers for Electrolytic Capacitors-
http://www.cde.com/tech/multipliers.pdf