Lifetime Testing of Metallized Thin Film Capacitors for Inverter Applications

Jack Flicker, Robert Kaplar, Matthew Marinella, and Jennifer Granata

SANDIA NATIONAL LABORATORIES, ALBUQUERQUE/NM, 87185, USA

Abstract — **In order to understand the degradation mechanisms and failure precursors of metallized thin film capacitors (MTFC) used in photovoltaic (PV) inverters, we have carried out accelerated testing on MTFCs. By understanding the degradation mechanisms and precursors of imminent catastrophic failure, implementation of a prognostics and health management (PHM) plan can be used to optimize PV array operations and maintenance (O&M), decreasing cost per watt towards the US Department of Energy goals.**

Index Terms — **PV systems, inverter reliability, capacitors.**

I. INTRODUCTION

In PV inverters, the combination of semiconductor switching and PV array source inductance results in an additional AC component injected onto the nominally DC bus. This AC component is known as voltage ripple (V^{ripple}) and exists throughout the inverter/module circuit. The PV module is hypersensitive to V^{ripple} as voltage ripple dramatically reduces available output power [1].

In order to limit this voltage ripple, each inverter requires an energy storage element (i.e. a capacitor) [2]. Many consider these DC bus capacitors to be the weak link in inverter reliability [3] due to constant temperature and power cycling and high internal capacitor temperatures. According to SunEdison, over a 27-month period, capacitor issues were responsible for 7% of inverter energy loss due to maintenance and downtime [4]. Therefore, a thorough knowledge of capacitor degradation and failure is important to both increasing capacitor lifetime through improved inverter design and optimizing O&M to decrease PV array costs.

Historically, electrolytic capacitors have been used as the bus capacitor due to their low cost and high capacitance per unit volume. Unfortunately, the use of liquid electrolyte means that these types of capacitors tend to suffer from high instability with temperature and time and large equivalent series resistance (ESR), yielding short lifetimes and the tendency to catastrophically fail while releasing H_2 gas [5].

In recent years, inverter manufacturers, especially those in utility scale systems, have been moving towards MTFCs. These capacitors consist of a dielectric plastic film (10-100 μm), which is metallized on both sides with Al and/or Zn (~20-100 nm) in pure or alloyed states to form electrodes [6]. Though a variety of polymer film dielectrics can be used, the majority of high performance capacitors utilize biaxially oriented polypropylene film as the dielectric due to low cost, low resistance, and high manufacturing consistency [7]. MTFCs are thought to have longer lifetimes than electrolytic capacitors for a number of reasons including better reverse/over voltage handling, smaller internal heating due to lower ESR, and clearing behavior (described below).

Clearing is a mechanism found in MTFCs due to the thin electrode. In this mechanism, during capacitor operation, defects in the dielectric film will short and locally heat at some applied voltage less than the global breakdown voltage of the device. The nm-scale electrode layer will quickly heat via Joule heating and vaporize, isolating the local defect region through the creation of a pinhole (~5-8 mm^2 [8]) in the electrode. The capacitor suffers a small decrease in capacitance, but lifetime is increased by avoiding catastrophic failure. Eventually it is assumed that the capacitor suffers a "soft" failure after capacitor degradation yields a certain percentage of capacitance degradation (the definition of soft failure varies by manufacturer and application).

Due to soft failure, MTFCs are thought to be inherently safer than electrolytics and offer potential improvements to inverter safety and reliability [9-12]. However, as more clearing events occur, the production of vaporized metal increases pressure inside the casing. This increase in pressure tends to increase the rate of degradation [13] as localized failure in one area leaves neighboring areas ripe for further electrical breakdown (Fig. 1) [8]. The eventual build-up of metallized vapor can cause catastrophic failure either through the pressure increasing enough to burst the capacitor casing [14] or the vaporized metal concentration increasing enough to become conductive and cause a flashover event [15].

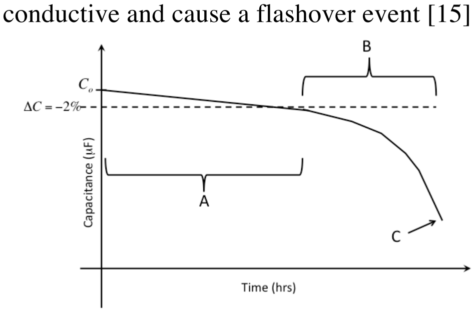

Fig. 1. Typical capacitance degradation over time of an MTFC. Clearing events result in a steady decrease in capacitance until soft failure (A, ΔC=2% in this case). Sometime after soft failure, the degradation rate increases (B) until the conductive vapor inside the MTFC leads to catastrophic failure (C).

In this work, we conduct accelerated testing on MTFCs to demonstrate increased degradation rates over time and eventual catastrophic failure. The electrical performance over time of stressed capacitors is analyzed in order to determine precursors to MTFC failure. By understanding the precursors of failure, it is possible to develop a suitable PHM scheme to decrease O&M costs for a PV array and therefore decrease the cost per watt of PV energy.

II. EXPERIMENTAL PROCEDURE

To safely test the high voltage, large capacitance (1 kV, 1 mF) devices typically used in PV inverters, a test setup was constructed as shown in Fig. 2. The capacitor under test is enclosed in a two-box design. Once the outer plexiglass box is breached, an auto-shunt circuit discharges the capacitor via a brass bar through a 5 kΩ (100 W) resistor before a user can contact the capacitor inside the inner plexiglass box.

The capacitor under test is stressed by temperature and/or voltage through the use of a Kiethley 7001 high voltage switch matrix card. Temperature control is provided by an Omega CN740 temperature controller with an SRT051-40 tape heater and an SA2C-J J-type thermocouple. DC voltage stress is provided by a Kiethley 2410 power supply. Electrical measurements of capacitance and ESR are taken via an Agilent 4263B LCR meter.

To safely measure the electrical characteristics with an LCR meter, the capacitor must be completely discharged through a bank of resistors. In order to minimize discharge time while still limiting current through the switch matrix (10 VA max), resistance steps of 100 kΩ, 50 kΩ, 4.5 kΩ, and 20 mΩ were used by the combination of multiple resistors in parallel.

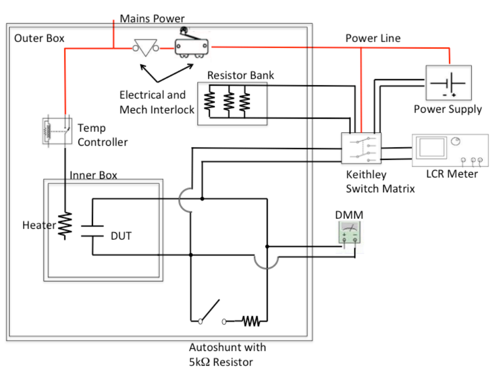

Fig. 2. Circuit schematic of capacitor accelerated-aging test setup. The user is protected with a dual Plexiglas box system with automatic shunt and both electrical and mechanical interlocks. The capacitor can be accelerated by voltage and temperature.

In order to test the electrical degradation of a MTFC under voltage and temperature stress, an 800 V, 600 mF polypropylene capacitor with a listed lifetime of 200,000 hours at rated voltage and 60ºC (5,000 hours at rated voltage and 85ºC) was tested at voltages of 850 and 900 V and temperatures of 25ºC, 50ºC, and 80ºC.

The capacitor under test was charged to the holding voltage with a maximum current flow of 10 mA and held at that voltage for 30 minutes. After the 30-minute holding period, the capacitor was discharged through the resistor bank in under two minutes. Once the capacitor is fully discharged, five averaged measurements of the capacitance and ESR are taken using the LCR meter. The capacitor is then charged and the process is repeated until failure.

III. RESULTS AND DISCUSSION

After 901 hours of testing at 900V and 85ºC (1,513 hours total), the capacitor demonstrated catastrophic failure (Fig. 3). As a result catastrophic failure, the capacitor packaging was breached and the encapsulant can be seen. Although it cannot be determined using this setup if catastrophic failure was due to pressure build-up or flashover, the expansion of encapsulant indicates internal heating of the capacitor, which suggests failure due to flashover.

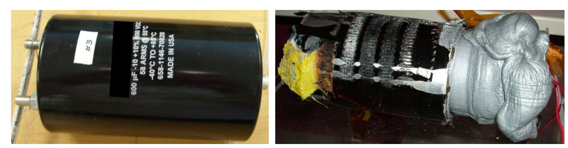

Fig. 3. (left) 800V, 600μF MTFC before accelerated test. (right) After accelerated testing, MTFC packaging has burst in a catastrophic failure and encapsulant has expanded out of the can.

The results of electrical measurements during testing of capacitance and ESR over time are shown in Fig. 4 and Fig. 5, respectively. The capacitance data looks similar to the degradation that is expected from a MTFC. There is a long period of slow, steady degradation following by a period of accelerating degradation. Shortly after the capacitor passes the degradation failure point (defined by the manufacturer as 98% of original capacitance), the capacitor catastrophically fails.

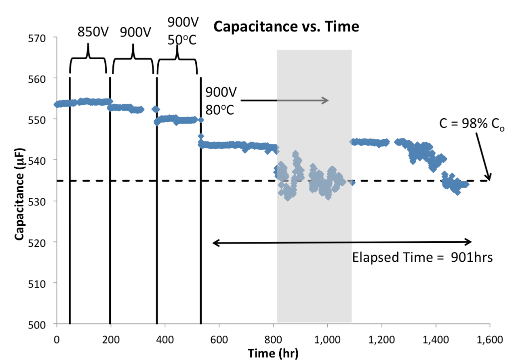

Fig. 4. MTFC capacitance over time during an accelerated lifetime test (voltages and temperatures indicated). The grey box indicates faulty reading due to a loose connection. Following degradation failure (dashed line) the capacitor catastrophically failed.

In addition to the characteristic degradation of the MTFC capacitance, the ESR also demonstrates degradation. For much of the testing period, the ESR stays below 10 mΩ. Simultaneously with the period of accelerating capacitance degradation occurs (approximately 1,200-1,400 hours), the ESR increases dramatically to around 38 mΩ.

This increase in ESR is closely tied to the accelerating capacitance degradation due to a positive feedback mechanism. A larger ESR yields more internal heating during charge/discharge or in response to DC bus ripple. The internal heating yields more degradation, which increases the ESR as the process repeats itself, eventually leading to failure. In addition to being closely tied to the degradation of the capacitor, ESR is an easier quantity to measure *in situ* than capacitance. Therefore, with appropriate sensor data, a large ESR increase could be used in a PHM scheme to signal imminent catastrophic failure of an MTFC used in the field.

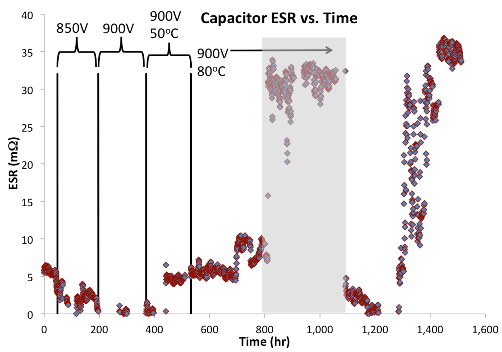

Fig. 5. MTFC ESR over time during accelerated lifetime testing. The grey box indicates faulty reading due to a loose connection. Prior to catastrophic failure the capacitor demonstrated a rapid and large ESR increase.

IV. CONCLUSION

Capacitors are critical to the operation of PV systems because they control voltage ripple on the DC bus, maintaining the operation point of the PV system. Since these capacitors are a significant issue in terms of reliability, there has been a trend towards replacing electrolytic capacitors with metallized thin film capacitors.

Sandia National Labs has built a test setup to perform accelerated lifetime testing of large MTFCs. This testing has resulted in capacitors that demonstrate both capacitance and ESR degradation in response to temperature and voltage stress. Additionally, MTFCs have been shown to catastrophically fail though continued use past the soft failure point. Future work will consist of testing a larger statistical sampling of MTFCs in order to develop knowledge of precursors to failure that could be used in a PHM scheme to optimize O&M, thereby decreasing the operating costs of PV arrays.

ACKNOWLEDGEMENTS

This work was funded by the DOE Office of Energy Efficiency and Renewable Energy. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

REFERENCES

[1] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules," *IEEE Transactions on Industry Applications,* vol. 41 (5), pp. 1292-1306, 2005.

[2] C. Siedle and V. D. Ingenieure, *Comparative Investigations of Charge Equalizers to Improve the Long-Term Performance of Multi-cell Battery Banks* vol. 245: VDI Verlag, 1998.

[3] Y. Xue, K. C. Divya, G. Griepentrog, M. Liviu, S. Suresh, and M. Manjrekar, "Towards Next Generation Photovoltaic Inverters," 2011 IEEE Energy Conversion Congress and Exposition (ECCE), 2011.

[4] A. Kaushik and A. Golnas, "Proceedings of SPIE," Reliability of Photovoltaic Cells, Modules, Components, and Systems IV, 2011.

[5] J. Ho, T. R. Jow, and S. Boggs, "Historical Introduction to Capacitor Technology," *IEEE Electrical Insulation Magazine,* vol. 26 (1), pp. 20-25, 2010.

[6] L. Hua, L. Fuchang, Z. Heqing, D. Ling, H. Yongxia, and K. Zhonghua, "Study on Metallized Film Capacitor and Its Voltage Maintaining Performance," *IEEE Transactions on Magnetics,* vol. 45 (1), pp. 327-330, 2009.

[7] N. Henze and J. Liu, "Reliability Considerations of Low-Power Grid-Tied Inverter for Photovoltaic Application," 24th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 2009.

[8] C. W. Reed and S. W. Cichanowskil, "The Fundamentals of Aging in HV Polymer-film Capacitors," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 1 (5), pp. 904-922, 1994.

[9] L. Gu, X. Ruan, M. Xu, and K. Yao, "Means of Eliminating Electrolytic Capacitor in AC/DC Power Supplies for LED Lightings," *IEEE Transactions on Power Electronics,* vol. 24 (5), pp. 1399-1408, Jun 2009.

[10] J.-S. Lai, H. Kouns, and J. Bond, "A low-inductance DC bus capacitor for high power traction motor drive inverters," Industry Applications Conference, 2002. 37th IAS Annual Meeting. Conference Record of the, 2002.

[11] R. Mirzahosseini and F. Tahami, "A lifetime improved single phase grid connected photovoltaic inverter," *Power Electronics and Drive Systems Technology (PEDSTC), 2012 3rd,* pp. 234-238, 2012.

[12] J. Worden and M. Zuercher-Martinson. (2009, May) How Inverters Work. *SolarPro*. 68-85.

[13] W. Sarjeant, J. Zirnheld, and F. MacDougall, "Capacitors," *IEEE Transactions on Plasma Science,* vol. 26 (5), pp. 1368-1392, 1998.

[14] W. Sarjeant, F. MacDougall, D. Larson, and I. Kohlberg, "Energy storage capacitors: Aging, and diagnostic approaches for life validation," IEEE Transactions on Magnetics, 1997.

[15] A. Schneuwly, P. Groning, and L. Schlapbach, "Uncoupling Behaviour of Current Gates in Self-healing Capacitors," *Materials Science and Engineering B-Solid State Materials for Advanced Technology,* vol. 55 (3), pp. 210-220, 1998.