Chill Out: Freezing Attacks on Capacitors and DC/DC Converters

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***Abstract*—This paper introduces a non-invasive, low-cost, and trace-free capacitor freezing attack on DC/DC converters, which uses off-the-shelf electronics cooling sprays to rapidly decrease the capacitors' temperature. Due to the temperature drop, the converters are unable to maintain their specified output voltages, and their transient behavior changes. When the attack has finished, the temperature of the capacitors quickly returns to normal, while any evidence of the attack vanishes.**

***Index Terms*—Electrolytic Capacitors, DC/DC Converters, Cooling Spray, Freezing Attacks, Hardware Security**

I. INTRODUCTION

Capacitors are an integral part of DC/DC converters, both on the input side to reduce input ripple voltage [5], and on the output side to ensure stable voltage levels in the presence of varying loads [2]. However, capacitors are not entirely stable over all possible operating temperatures. For example, the capacitance of electrolytic capacitors can decrease by almost 40% when exposed to low temperatures of $-55\,^{\circ}\mathrm{C}$ [2], [4], potentially affecting the transient response of DC/DC converters using such capacitors, and hence the security of the system as a whole.

This work explores the effects of using off-the-shelf, low-cost cooling sprays on electrolytic capacitors in isolation and in DC/DC converter modules. We investigate how a capacitor's physical and electrical properties influence how effective cooling sprays are in changing the capacitor's characteristics. We further study the impact of the cooling duration on the measured capacitance, and show that the behavior of capacitors changes, even when they are cooled for as little as 10–30 s. Once the cooling effect wears off, the system returns to normal, while any traces of the spraying process disappear.

II. EXPERIMENTAL SETUP

In this work, we use two basic circuit designs: one to assess changes to capacitor behavior in response to cooling, and another to demonstrate the impact of capacitor cooling on standard DC/DC converter circuits.

The *capacitor cooling* setup uses the ADALM2000 power supply and oscilloscope module to drive the capacitors with 3–5 V and capture each capacitor's charging and discharging time under different cooling conditions. The charging and discharging time is estimated by reading the voltage across each capacitor in response to turning the output of the power supply on or off, computing the RC constant of the response from the data, and then extracting the computed capacitance using the known value of the circuit's resistance.

The *DC/DC converter* setup uses a Keithley 2231A power supply to provide a 12 V input to two off-the-shelf converters, one built around XLSEMI's XL4015 chip, and the other around Texas Instruments' LM2596 module. We measure the transient response of the step-down regulators using a Tektronix MDO3104 Mixed Domain Oscilloscope with TPP1000 1 GHz passive probes by reading the output voltage of the converter module in response to an increase in current imposed by an N-Channel MOSFET.

For both experimental setups, capacitors with a rating of 16–50 V, capacitance of 220–1,500 µF, and different physical dimensions are used. Two different cooling sprays are employed: a 10 oz Walmart Onn Electronics Duster containing difluoroethane (HFC-152a) in liquid state, and a 10 oz 403A-285G Super Cold 134A produced by MG Chemicals containing tetrafluoroethane (HFC-134a), which, when sprayed onto a device, is expected to chill down to $-51\,^{\circ}\mathrm{C}$ ($-60\,^{\circ}\mathrm{F}$).

III. EVALUATION OF CAPACITOR COOLING

Figure 1 shows the percentage change in capacitance as a function of the duration of the cooling for different capacitors. The baseline capacitance was measured at room temperature (i.e., a cooling time of 0 s), and then the changes in capacitance were measured after cooling durations of 10 s, 20 s, and 30 s. Experiments were spread out by several minutes to ensure the capacitor's temperature returned to normal, and were repeated four times. This change was computed relative to the baseline capacitance at room temperature, and the baseline was within the manufacturing tolerance limits of the capacitors. Capacitors with larger capacitances, which tend to be physically larger as well, experience smaller capacitance changes, likely because it is hard to effectively and consistently cool the entire capacitor area with the cooling spray. Results were nearly identical when testing with either cooling spray.

Figure 2 shows the impact of the capacitor's physical size on the cooling effect. Two 220 µF capacitors from the same

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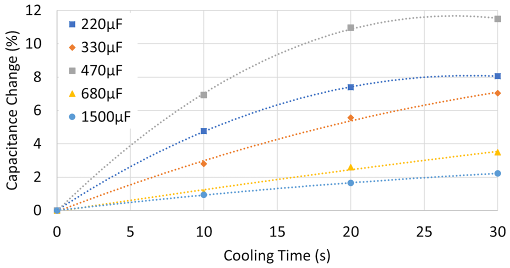


Fig. 1. Percentage change in the capacitance of different aluminum electrolytic capacitors when cooled with the spray.

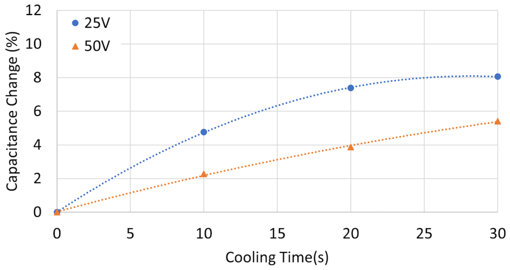


Fig. 2. Percentage change in the capacitance of two 220 µF capacitors with different voltage ratings and sizes as a function of cooling time.

manufacturer, but with different sizes (volumes of approximately 580 mm^3 and 900 mm^3) and voltage ratings (of 25 V and 50 V) were used. Higher-rated capacitors tend to be bigger, as the breakdown voltage increases with the thickness (separation) between the capacitor plates [1]. This experiment confirms that the smaller 25 V capacitor experiences a more pronounced change compared to the larger 50 V one.

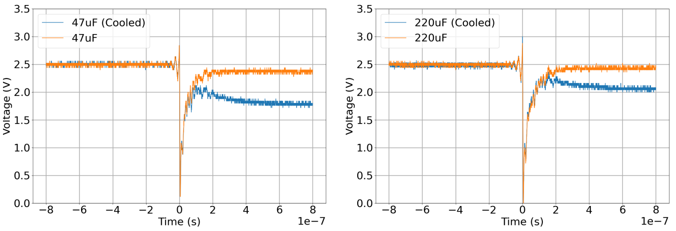
IV. EVALUATION OF DC/DC CONVERTER COOLING

The transient response and voltage sag of the XL4015 DC/DC converter before and after its output capacitor has been cooled for 30 s is shown in Figures 3a and 3b. The output capacitor of the XL4015 in these experiments has been replaced with a 47 µF and 220 µF aluminum electrolytic capacitor respectively. As the figures show, cooling the capacitor has a significant impact on the output voltage. However, the voltage sag is more prominent in the smaller, 47 µF capacitor compared to the larger, 220 µF one.

In general, smaller capacitors are unable to maintain the target voltage value in the presence of a large load, even without the effect of the cooling spray. When cooled, the capacitance is reduced to a point that voltage sag becomes excessive: the voltage sag of the smaller, 47 µF capacitor (Figure 3a) is 1.6× greater than that of the larger, 220 µF one (Figure 3b), at −694 mV as opposed to −425 mV. In the other direction, the effect almost vanishes completely when testing with an even bigger capacitor of 470 µF.

V. SECURITY DISCUSSION

Other types of capacitors are less susceptible to extreme temperature changes. For example, when we replaced the output aluminum electrolytic capacitor with a tantalum capacitor of equal value, there was no noticeable change in the behavior of the XL4015 DC/DC converter when cooled. However, tantalum capacitors can be more expensive, and generally support smaller voltage ranges. Moreover, the output voltage took longer to stabilize, so simply changing the capacitor type may have other unintended consequences for the converter.



(a) 47 µF

(b) 220 µF

Fig. 3. Transient response for the XL4015 DC/DC converter before and after cooling with (a) a 47 µF or (b) a 220 µF output capacitor.

To evaluate the stealthiness of the freezing attack on the transient response of DC/DC converters, we measured how long it takes for the capacitor to return back to room temperature. Capacitors were sprayed for 30 s, and a Klein Tools IR1000 infrared (IR) thermometer measured their external temperature as −40 °C. Any frost that had formed on the capacitor dissipated after about 5–10 min, and temperature returned close to room temperature in the same timeframe. After approximately 30 min, the temperature had fully returned to normal, even when the DC/DC converter was not active.

Overall, cooling capacitors can force circuits to operate outside their limits, and therefore presents a novel security threat. We hope to use this effect in future work to implement Hardware Trojans that can activate on-chip voltage monitors that detect short-lived voltage drops [3].

VI. CONCLUSION

This work explored the effects of using off-the-shelf, low-cost electronic cooling sprays on the behavior of capacitors and DC/DC converters. It characterized how the capacitance of aluminum electrolytic capacitors changes as a function of cooling time, rather than absolute temperature, and showed that a freezing attack using cooling sprays can impact the transient response of DC/DC converters. Overall, this work highlighted that components such as DC/DC converters can be the sources of new attacks on the security and reliability of computer and embedded systems.

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