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Capacitors' leakage current measurement for energy harvesting applications

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Annotation:
The paper presents a USB measuring device, that can be used for characterization of the self-discharging properties of an electrolytical capacitor. It is basically a voltmeter with very high input impedance and very low input current, so just the leakage current of the capacitor affects its voltage. It is based on an instrumentation amplifier AD8422 with input impedance 200 GΩ and input bias current lower than 1 nA. Its functionality is demonstrated on measurement of electrolytical capacitors that were treated at different conditions (new/old capacitors, quick/slow charging, long-term treatment at the forming voltage). Main purpose of the device is to measure the leakage current of the storage capacitors when energy harvesting is applied. If weak energy sources are harvested, the storage capacitor's leakage current is an important parameter to be considered in the design. The paper also presents method how the storage capacitor must be treated to minimize the leakage current.

Anotace:
Článek představuje měřicí zařízení, které lze použít k charakterizaci samo-vybíjecích proudů elektrolytického kondenzátoru. Jedná se v podstatě o voltmetr s velmi vysokou vstupní impedancí a velmi malým vstupním proudem, takže jeho napětí ovlivňuje pouze svodový proud kondenzátoru. Je založen na přístrojovém zesilovači AD8422 se vstupní impedancí 200 GΩ a vstupním svodovým proudem menším než 1 nA. Jeho funkčnost je demonstrována na měření elektrolytických kondenzátorů, které byly ošetřeny za různých podmínek (nové/staré kondenzátory, rychlé/pomalé nabíjení, dlouhodobé ošetření na formovacím napětí). Hlavním účelem zařízení je měření svodového proudu akumulačních kondenzátorů, které se používají při napájení zařízení pomocí energie z okolí. Pokud jsou pro tento účel použity slabé zdroje energie (například piezoelektrický generátor), je svodový proud akumulačního kondenzátoru důležitým parametrem, který je třeba při návrhu zohlednit. V článku je rovněž uvedena metoda, jak je třeba akumulační kondenzátor ošetřit, aby se jeho svodový proud minimalizoval.

INTRODUCTION

The leakage current of the capacitor is essential parameter for many practical applications that deal with energy harvesting. When the small currents are harvested (e.g. piezoelectric harvesters), the leakage of the storage capacitor can significantly affect the efficiency of such kind of a powering. Knowing the actual leakage current can help to select proper storage capacitor for given application. The paper presents a USB measuring device, that can be used for characterization of the self-discharging properties of an electrolytical capacitor that is connected in the application.

ENERGY HARVESTER MODULE

As a representative energy harvester can be considered a module EH300 [1] that is able to harvest energy from the sources with high internal resistance. Input currents can be in the range from 200 nA to 400 mA and it can be harvested to the build-in 1 mF storage capacitor or also an external capacitors can be connected.

The voltage on the capacitor is released in the range of voltages 1.8 V – 3.6 V. Its operational principle is following (see Fig. 1). The harvester EH300 stores the energy from energy source to the capacitor while the load is disconnected. When it is charged to 3.6 V (V_H), the capacitor is connected to the output port and the accumulated energy is provided to the load. The energy is available until the voltage on the capacitor drops down to 1.8 V (V_L) and it is disconnected. When the harvester's output is closed the energy from the energy source can be harvested again. For 1 mF capacitor the energy released in one charging cycle is 4.9 mJ.

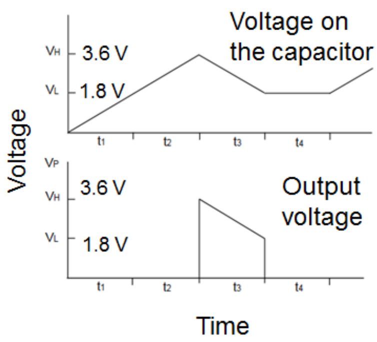

Fig. 1: Operating cycle of the harvester EH300 [1]

As it will be demonstrated later, the leakage current of the storage capacitor can be very high and it should be considered especially when the weak energy sources are harvested. The presented characterization device allows to measure the leakage current of the harvester (storage capacitor) that is connected directly in the application. Knowing the actual leakage current can help to select proper storage capacitor for given application.

CHARACTERIZATION DEVICE

The characterization device is a voltmeter with very high input impedance and very low input current, so just the leakage current of the capacitor affects its voltage. It is based on an instrumentation amplifier AD8422 [2] with input impedance 200 GΩ and input bias current lower than 1 nA. Figure 2 presents the analogue part of the device, where the instrumentation amplifier is connected to the 16 bits analogue to digital converter (ADC).

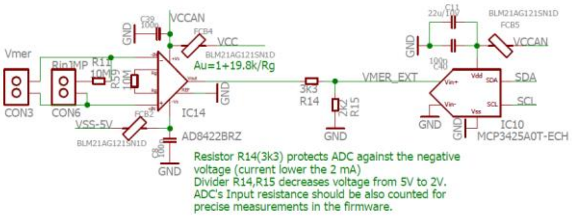

Fig.2: Schematic of the analogue part of the measuring device

The voltage is later processed by MCU and sent to the USB port. The data are logged to the PC at selectable rates starting from 1 second up to 1 hour. Figure 3 shows the device connected to the measured capacitor and figure 4 shows logged data on PC.

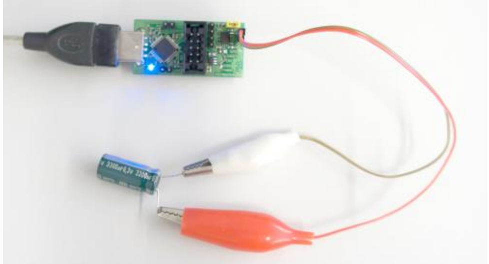

Fig.3: USB device with the capacitor under test

The capacitor under test is charged to a maximum voltage and then its self-discharging is checked using the voltmeter with negligible input impedance. The voltage decrease in time is recorded to PC. The voltage drop can be used for calculation of the equivalent leakage current I_{leak} (A) using the equation (1), where C (F) is capacity of the capacitor, ΔV_C (V) is the voltage drop on the capacitor during the time interval ΔT (s).

$$I_{leak} \approx \frac{\Delta V_C \cdot C}{\Delta T} \qquad (1)$$

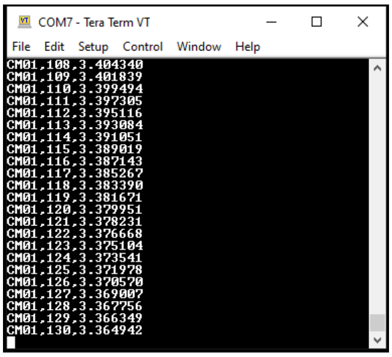

Fig.4: Logged data from the device in Tera Term on PC

MEASURED DATA

The leakage current of the capacitor is affected by many parameters such as temperature, voltage rating, previous state, ageing, etc. [3, 4, 5, 6]. To minimize the leakage, it is important to obey the following principles:

- the capacity should be optimal for the given application (e.g., not too large),
- a high-quality capacitor should be used (e.g., low leakage series),
- a high temperature rate capacitor should be used,
- a high voltage rating capacitor should be used as the leakage current increases exponentially when the operating voltage exceeds the rated voltage and approaches the forming voltage,
- the capacitor should be new or well formatted (older capacitors should be treated at least 24 hours at the maximal rated voltage)

When the electrolytic capacitor is charged by a high current peak, the leakage current is initially very high and slowly decreases over time to its steady value (Curie–von Schweidler law). This effect should be considered when the high current impulses are harvested.

Following graphs in figures 5 – 10 present a measurement results of different capacitors that were treated at different conditions before the measurement.

First, the several years old capacitor 3300 μF/6.3 V from the figure 3 was connected. It was measured three times. Still line in the graphs (Figures 5 and 6) called “No formatted” represent measurement when the capacitor was charged directly after it was taken out from the socket (several years old). Then the capacitor was formatted 24 hours at the voltage close to its forming voltage and then the voltage was disconnected to allow the discharge (dotted line “Formatted, slowly charged”). The third curves belong to formatted capacitor that was discharged to zero and then quickly charged by high current peak (dash line "Formatted, quickly charged").

Table 1 summarizes the leakage currents of this capacitor. The initial leakage current was up to 60 µA. After reformatting the leakage dropped to its steady value 17 nA @ 21 °C. When the electrolytical capacitor is charged by a high current peak, the leakage current is initially high (3 µA) and then decreases to its steady value (Curie–von Schweidler law [3]). This effect should be considered when the high current impulses are harvested and the storage capacitor should be always new or well formatted (older capacitors should be treated at least 24 hours at the maximal rated voltage)

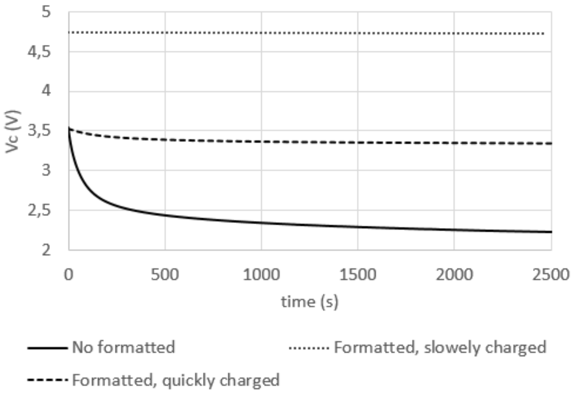

Fig.5: Voltage measurement on self-discharging capacitor 3 300 µF / 6.3 V at different conditions

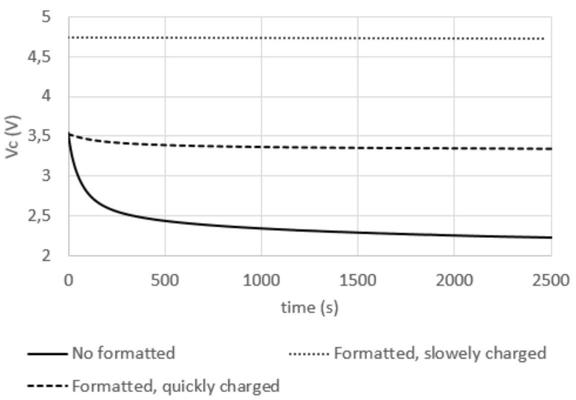

Fig.6: Calculation of the leakage current according to equation (1) for the capacitor 3 300 µF / 6.3 V at different conditions

Tab. 1: Capacitor 3 300 µF /6.3 V

Conditions	***Initial Leakage***	***Steady Leakage***
No formatted, quickly charged	58 µA	36 nA (1 hour)
Formatted, quickly charged	31 µA	25 nA (1 hour)
Formatted, slowly charged	17 nA	17 nA (1 hour)

Second capacitor under test was more than 30 years old component of capacity 10 mF / 6 V (figures 7, 8, table 2).

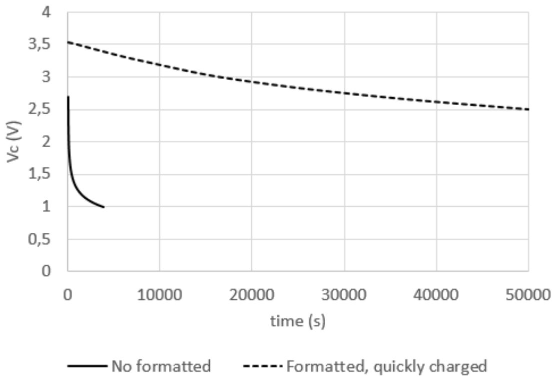

Fig.7: Voltage measurement on self-discharging capacitor 10 000 µF / 6 V at different conditions

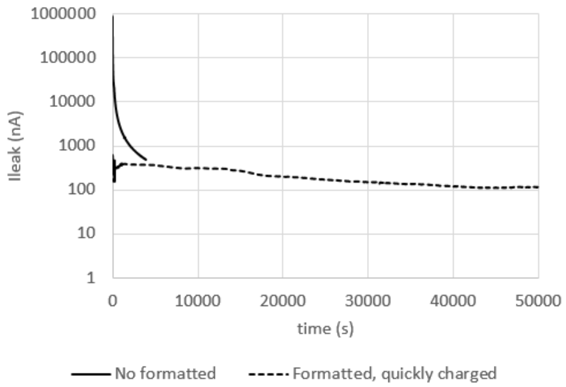

Fig.8: Calculation of the leakage current according to equation (1) for the capacitor 10 000 µF / 6 V at different conditions

Tab. 2: Capacitor 10 000 µF /6 V

Conditions	***Initial Leakage***	***Steady Leakage***
No formatted, quickly charged	891 µA	585 nA (1 hour)
Formatted, quickly charged	625 nA	100 nA (15 hours)

Initial leakage current after it was quickly charged was nearly 1 mA and the capacitor was useless for any kind of energy storage purposes. After it was treated 24 hours at the voltage 6 V, the leakage current decreased significantly down to 100 nA and only the Curie–von Schweidler effect was observable for high charging current peaks.

The third capacitor measured was the harvester EH 300. Measured data are presented in figures 9, 10 and in the table 3. The harvester module was new so just the Curie–von Schweidler effect was increasing the initial leakage current. Steady value of the leakage current (capacitor plus the module) was 17 nA. Nevertheless, the initial value of 3.9 µA is much larger than 200 nA declared in datasheet.

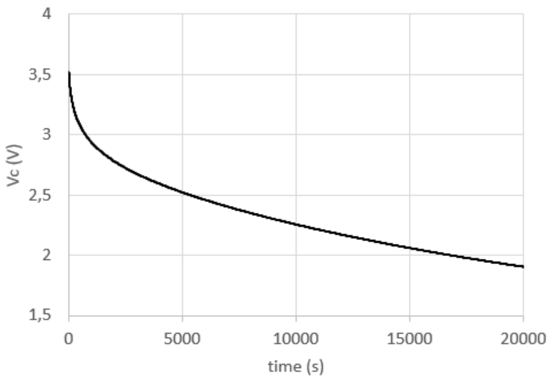

Fig.9: Voltage measurement on self-discharging capacitor 1 000 μF / 6.3 V on harvester module EH300

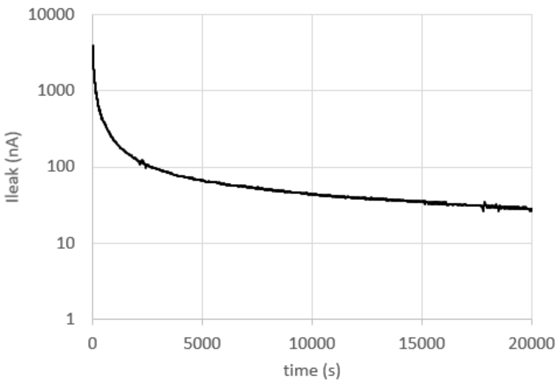

Fig.10: Calculation of the leakage current according to equation (1) for the capacitor 1 000 μF / 6.3 V on harvester module EH300 at different conditions

Tab. 3: Capacitor 1 000 μF /6.3 V on harvester module EH300

Conditions	*Initial Leakage*	*Steady Leakage*
No formatted, quickly charged	3.9 μA	26 nA (5 hours)

CONCLUSIONS

Characterization device for capacitors' leakage current was presented. Knowledge of the leakage current is important especially when the weak energy sources are harvested. Presented device has a form of USB dongle and thus it allows measurement at working conditions of the harvester. Its functionality was demonstrated on three different capacitors and it proved, that proper treatment of the capacitor is needed for minimizing the leakage.

ACKNOWLEDGMENTS

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