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NON-SAMPLING CURRENT MEASUREMENT FOR MICROAMPERE RANGES

Bachelor’s Thesis
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ABSTRACT

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The purpose of this thesis was to study an alternative method for measuring the average current consumption of a low power embedded system. Traditionally, a shunt resistor is used to periodically sample the momentary current draw, and these samples are then averaged to find the average consumption. The sampling method works well when consumption is constant, however, if the consumption changes quickly, a high sampling frequency is needed to capture all the changes accurately. In this alternative method, current is measured by charging up a capacitor, powering the Device Under Testing from the capacitor and measuring how long it takes to discharge the capacitor by a certain voltage. This eliminates the problem of sampling frequency. According to the formula of capacitance, a capacitor relates a voltage to an amount of charge stored in the capacitor. If a capacitor is discharged by a known voltage, the number of chargers that were released can be calculated, given that the capacitance is known. Then, by measuring the time it takes to release the charges, a current value can be calculated by dividing the number of charges by the measured time, which results in the average current consumption during the measured time. In theory, the consumption during the measurement period should be captured perfectly.

A measurement device using this style of measurement was built. The device was designed to measure an average current of 50 µA for 40 seconds to obtain a good average from a varying consumption profile. The accuracy and precision of the device was then measured by connecting resistors as the load and calculating what the ideal consumption reading for the given resistance would be. Then the current consumption of the resistor was measured and compared to the ideal number to find the accuracy. The precision was measured by repeating the measurement with multiple devices and calculating the standard deviation. The accuracy of the device remained within 3 % when measuring in a range of 10 µA to 500 µA. The standard deviation was generally within ± 1 %.

The device employed electrolytic capacitors for the main measurement capacitor, which added challenges to the timing of the measurements. Electrolytic capacitors exhibit a behaviour where they don't fully charge immediately after being connected to power but take minutes or even hours to reach their maximum charge. This phenomenon is called dielectric absorption. The same applies for discharging, when discharged quickly, they don't release all their charge and the capacitance appears smaller, which increases the current reading. Especially for smaller currents, around 1 µA, the measurement result was quite sensitive to how long the device was powered on before starting the measurement. The result changed around 30% between starting the measurement immediately after being powered, and having the capacitor powered for 10 hours before measuring. Although, when measuring very small currents, less capacitance is needed. If the device can be designed for the smaller currents, it may be possible to utilize ceramic or plastic capacitors instead. These capacitor types exhibit less dielectric absorption, which should help the accuracy of the measurements significantly.

Keywords: Electric current, current measurement, current meter, capacitor, electronics, testing, embedded system.

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TIIVISTELMÄ

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Työn tarkoituksena oli tutkia yritykselle suunnitellun virtamittarin tarkkuuta eri virroilla ja eri lämpötiloissa. Työssä esitellään hieman epätavallisempi tapa mitata sähkövirtaa, joka poikkeaa perinteisestä näytteistävästä mittaustavasta merkittävästi. Useimmiten virtaa mitataan kytkemällä kuorman kanssa sarjaan pieni vastus, ja virran hetkellinen suuruus lasketaan vastuksen yli tapahtuvasta jännitehäviöstä [1][2]. Mahdolliset keskiarvot lasketaan tilastollisesti useasta otetusta näytteestä. Näytteistävä mittaustapa on haasteellinen erityisesti piikkimäistä virrankulutusta mitatessa, sillä kahden näytteen välissä virran suuruus voi muuttua paljon, etenkin jos näytetaajuus ei ole riittävän tiheä. Tässä työssä esitellään tapa mitata virran keskiarvo ilman tilastollisia menetelmiä.

Mittausmenetelmän teoria perustuu sähkövirran ja kapasitanssin määritelmiin. Sähkövirta I kuvaa siirtyneiden varauksien, eli elektronien, määrää q ajanjaksoa t kohden. Hetkellinen sähkövirta, äärettömän pienenä ajanhetkenä $\mathrm{d}t$, on määritelty yhtälöllä

$$I = \frac{\mathrm{d}q}{\mathrm{d}t} \text{ [3]} \tag{1}$$

ja sähkövirran keskiarvo äärellisenä aikana Δt vastaavasti yhtälöllä

$$I = \frac{\Delta q}{\Delta t} \text{ [3].} \tag{2}$$

Symbolit $\mathrm{d}q$ ja Δq kuvaavat siirtyneiden elektronien määrää vastaavilla ajanjaksoillaan $\mathrm{d}t$ ja Δt. Kapasitanssi C puolestaan määritellään kondensaattoriin varastoituneiden varauksien määrän q ja sen terminaalien välisen sähköisen potentiaalin V suhteena yhtälön

$$C = \frac{q}{V} \text{ [3]} \tag{3}$$

mukaisesti. Tästä yhtälöstä voidaan ratkaista varaus kapasitanssin ja jännitteen funktiona seuraavasti:

$$q = CV. \tag{4}$$

Yhtälöstä voidaan johtaa myös, että jos kapasitanssi pysyy vakiona, voidaan varauksen muutosta kondensaattorissa kuvata jännitteen muutoksen funktiona

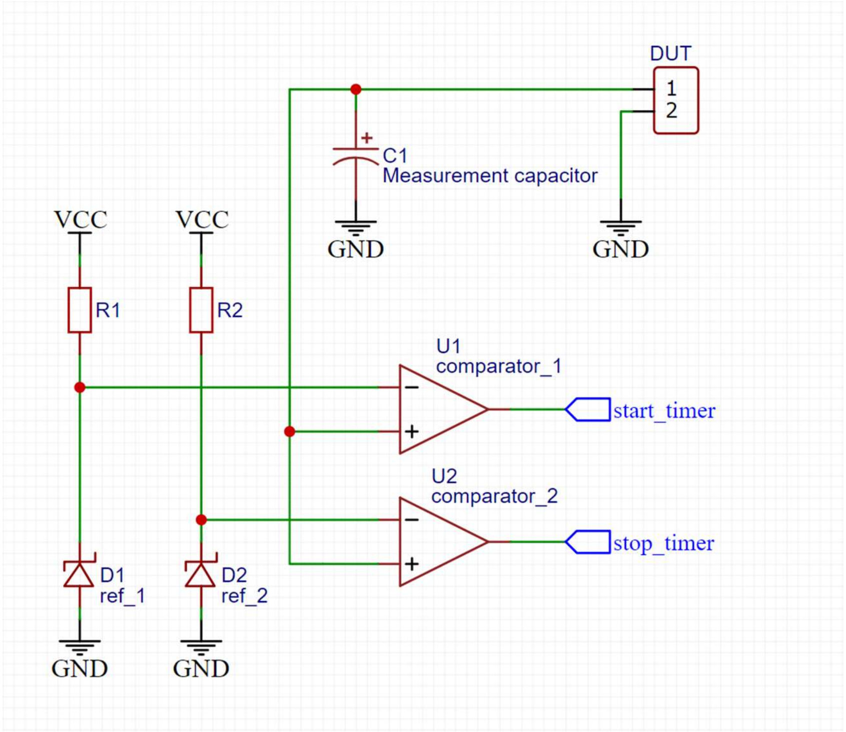
$$\Delta q = C\Delta V. \tag{5}$$

Tämä yhtälö voidaan nyt sijoittaa sähkövirran yhtälöön 2, jolloin saadaan keskimääräiselle virrankulutukselle lauseke

$$I = C\frac{\Delta V}{\Delta t}. \tag{6}$$

Yhtälö kuvaa kondensaattorin keskimääräistä purku- tai latausvirtaa kuluneena aikana Δt.

Teoriaa voi soveltaa käytäntöön lataamalla kondensaattori, kytkemällä se mitattavaan kuormaan, ja mittaamalla kuinka kauan kondensaattorilla kestää tyhjentyä. Yksi tapa toteuttaa tämä on vakioida kondensaattorista purettava jännite ΔV referenssien avulla, ja mitata purkamiseen kuluva aika Δt automaattisesti ja tarkasti esimerkiksi mikrokontrollerin ajastimella [4]. Jännitereferensseistä saadaan ajan mittaamiselle hyödylliset signaalit kytkemällä ne komparaattoreihin kuvan 1 osoittamalla tavalla.



Kuva 1. Kondensaattorin jännitteen vertailu referensseihin

Kuvan 1 komparaattoreiden ulostulosignaaleja käytetään ajastimen aloitus- ja lopetussignaaleina, ja siten saadaan yhteys jännitteen muutoksen ja ajan muutoksen välille. Yhtälö 6 on siis näin sovellettuna muotoa

$$I = C\frac{V_2 - V_1}{t_2 - t_1},$$

jossa V_2 ja V_1 ovat valitut jännitereferenssit ja t_2 sekä t_1 vastaavat ajanhetket, jolloin kondensaattorin laskeva jännite ohitti kyseiset referenssit.

Seuraavaksi esitellään mittauslaitteella saatuja mittaustuloksia. Mittauksissa käytettiin kuormana vastuksia, jotta kuorman ominaisuudet ovat mahdollisimman vakiot ja tunnetut. Mittauksissa käytettiin neljää mittauslaitetta, joiden tuloksista laskettiin keskiarvo sekä otoskeskihajonta. Käytetyistä vastuksista laskettiin laskennallinen virta-arvo yhtälöllä

$$I = \frac{-\Delta V}{R \times \ln\left(\frac{V_2}{V_1}\right)}, \tag{7}$$

joka saadaan yhdistämällä yhtälö 6, sekä kondensaattorin RC-laki $V_t = V_0 e^{-\frac{t}{RC}}$ $[3]$. Nämä laskennalliset virta-arvot edustavat tulosta, jonka mittari antaisi, jos se olisi täydellinen, eikä tuottaisi yhtään mittavirhettä. Todelliset mittaustulokset suhteutettiin laskennallisiin arvoihin, ja tuloksille laskettiin prosentuaalinen mittavirhe, jotta virheen määrää voidaan vertailla eri suuruusluokissa. Samoin otoshajonta suhteutettiin laskennalliseen virta-arvoon vertailukelpoisuuden vuoksi. Laitteet kalibroitiin 100 kΩ vastuksilla, joka vastaa yhtälöllä 7 laskettuna n. 51 mikroampeerin virtaa. Mitattavat virrat valittiin tämän kalibrointipisteen molemmin puolin. Taulukossa 1 on esitetty käytetyt vastukset, niiden nimellisarvot ja todelliset arvot, jotka mitattiin kuusinumeroisella, kalibroidulla yleismittarilla. Mittauskytkennässä käytettiin 2.2 mF:n elektrolyyttikondensaattoria, ja jännitereferenssit V_2 ja V_1 olivat 5.6 V sekä 4.7 V, eli $\Delta V = 0.9\mathrm{V}$.

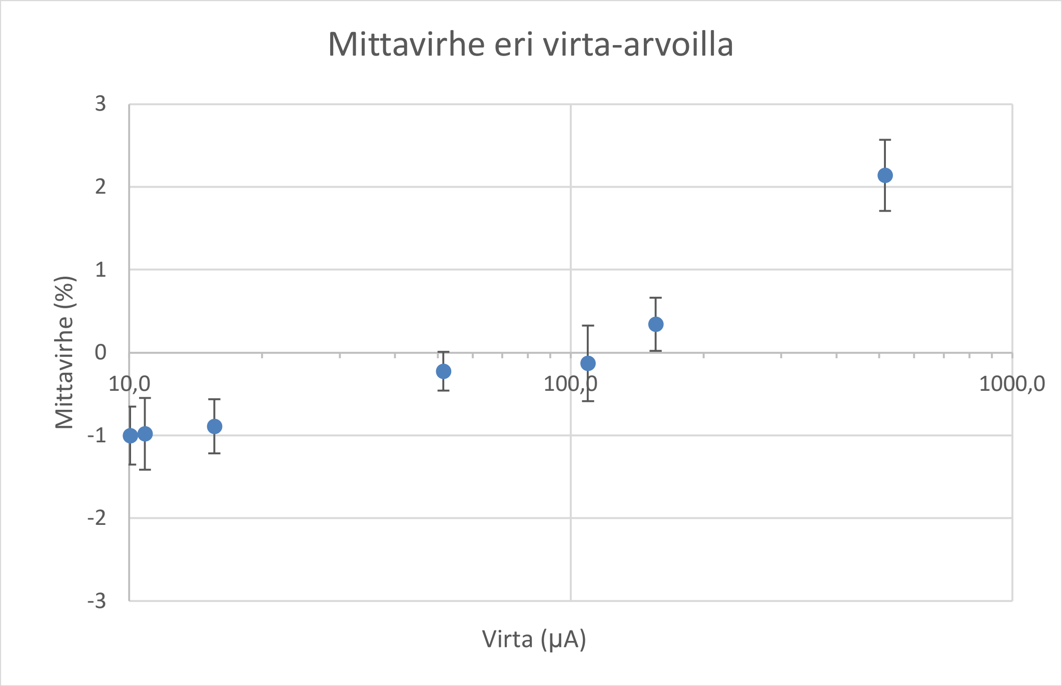
Taulukko 1. Käytetyt vastukset

Nimellisarvo (Ω)	Mitattu resistanssi (Ω)
10k	9970.2
33k	32989
47k	46959
100k	99768
330k	329550
470k	473270
510k	511410

Taulukossa 2 esitellään mittaustulokset, taulukon 1 vastusarvoista lasketut ideaaliset tulokset sekä lasketut virheet.

Taulukko 2. mittaustulokset

Laskennallinen (µA)	Tulosten keskiarvo (µA)	Virhe (%)	Otoshajonta (%)
513.7	526.25	2.45	0.43
155.7	156.25	0.34	0.32
109.4	109.25	-0.13	0.46
51.49	51.37	-0.22	0.23
15.59	15.45	-0.89	0.33
10.85	10.75	-0.98	0.43
10.04	9.94	-1.00	0.35



Kuva 2. Prosentuaalinen mittavirhe sekä otoskeskihajonta

Kuvassa 2 näkyy taulukon 2 tulokset, eli mittavirhe sekä hajonta. Kuvasta havaitaan, että mitä enemmän mitattavan virran suuruus poikkeaa virrasta, jolla laite on kalibroitu, sitä suurempi mittavirhe aiheutuu.

Mittavirhettä tulee muutamasta lähteestä, joiden painoarvo vaihtelee mitattavan virran suuruuden mukaan. Tunnistettuja virhelähteitä ovat mm. vuotovirrat, ajanmittauksen tarkkuus, sekä

dielektrisen absorption aiheuttamat vaikutukset. Suuria virtoja mitatessa mittausaika pienenee, sillä kondensaattori tyhjenee nopeammin. Esitellyissä mittauksissa aikaa mitattiin kahden millisekunnin (2 ms) resoluutiolla ohjelmassa toteutetulla kellolla. Suurimman virran mittauksessa mittausaika oli yhtälöstä 6 johdetun yhtälön

$$\Delta t = C\frac{\Delta V}{I} \tag{8}$$

avulla laskettuna noin

$$\begin{gathered} 2.2\mathrm{mF}\frac{0.9\mathrm{V}}{513.7\mathrm{\mu A}} \\ \approx 3854\ \mathrm{ms}. \end{gathered}$$

Mittausaika on jo niin pieni, että se ei välttämättä muodosta hyvää keskiarvoa mitattavan kohteen virrankulutuksesta. Mittausaikaa pystytäisiin pidentämään kapasitanssia kasvattamalla.

Pieniä virtoja mitatessa mittausaika kasvaa hyvin suureksi, jopa useihin minuutteihin, eli ajastimen tarkkuuden vaikutus muuttuu häviävän pieneksi, mutta vuotovirtojen vaikutus kasvaa huomattavasti. Todennäköisesti suurin vuotovirran lähde on kondensaattori, sillä piiriin ei ole kytketty kondensaattorin lisäksi muita komponentteja kuin komparaattori, jonka sisääntulojen vuotovirrat ovat vain 0.02 pA luokkaa [10], ja releen kontakti, jolla ei ole galvaanista yhteyttä muihin komponentteihin.

Yhteenvetona voidaan todeta, että hyvin mitoitettuna ja kalibroituna laite mittaa virtoja erittäin tarkasti, alle prosentin tarkkuudella, kalibrointipisteen läheisyydessä. Käyttökelpoisia mittaustuloksia saa noin kymmenen kertaa pienemmille ja kymmenen kertaa suuremmille arvoille kuin kalibrointivirta. Tämä mittaustapa ei kuitenkaan sovellu hyvin suurien virtojen mittaamiseen, sillä tarvittavien kondensaattoreiden fyysinen koko kasvaa hyvin suureksi ja mittauslaitteesta tulee kallis sekä hankalasti käsiteltävä. Pienille virroille laite soveltuu erinomaisesti, sillä pienemmälle virralle suunnitellussa mittauslaitteessa voidaan käyttää muovi- tai keraamikondensaattoreita, mikä parantaa mittaustarkkuutta pienempien vuotovirtojen ansiosta.

Avainsanat: sähkövirta, virtamittaus, virtamittari, elektroniikka, kondensaattori, testaus, sulautettu järjestelmä

PREFACE

The idea for the subject of this thesis was originally put forward by my project’s senior SW engineer Tom Höglund. He suggested to try to measure the very small current consumption of our development device by connecting a capacitor to the device and measuring how long it takes to discharge the capacitor to calculate the current consumption.

All schematic images have been produced by me, with the help of a free to use electronics design software known as EasyEDA, available at https://easyeda.com/.

Tampere, 09 May 2023

Olli Martikainen

CONTENTS

1. INTRODUCTION 1
2. THEORY OF OPERATION 3
    2.1 Equations 3
3. APPLYING THE PRINCIPLE 5
    3.1 Connecting and disconnecting the capacitor 6
    3.2 Selecting components 8
        3.2.1 Capacitor 8
        3.2.2 Comparator and voltage references 9
    3.3 PCB design considerations 10
    3.4 Calibration 10
    3.5 Example 12
4. MEASUREMENTS 13
    4.1 Dielectric absorption 14
    4.2 Temperature coefficient 20
5. ERROR STUDY 23
6. CONCLUSIONS 25
REFERENCES 27

LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

DUT	Device Under Testing
FPU	Floating Point Unit
MCU	Microcontroller Unit
PCB	Printed Circuit Board
VCC	Positive operating voltage

Symbols

A	Ampere, unit of current
α	Alpha, temperature coefficient
C	Capacitance
°C	Celsius, unit of temperature
F	Farad, unit of capacitance
I	Electric current
q	Electric charge
R	Resistance
s	Second, unit of time
T	Temperature
t	Time
U	Voltage
V	Volt, unit of voltage
Ω	Ohm, unit of resistance

1. INTRODUCTION

Most often current is measured by inserting a low resistance resistor, called a shunt resistor, in series with the load, and measuring the voltage difference across it. Current flowing through the shunt resistor causes a voltage drop, which can be amplified and measured to obtain the current. [1] In embedded systems, a microcontroller will periodically sample this voltage to calculate the instantaneous current. This thesis describes a continuous, non-sampling method for measuring the average current over a longer measurement time.

The motivation for the subject of the thesis stemmed from an embedded software development project. A company was producing software for an embedded device, which relies on a low idle running current to achieve a long battery change interval. Therefore, every software revision had to be tested to verify that the changes did not affect the current consumption of the device. The embedded system under development, or Device Under Testing (DUT), consumes current in short and sharp spikes of higher consumption between periods of extremely low consumption as shown in appendices 1 and 2. Consumption profiles like this are quite typical for low power applications where a Micro Controller Unit (MCU) is put into a sleep mode and woken up periodically to do work. This creates two requirements for the current measurement method: a high dynamic range, and high sampling frequency. Devices that fulfill these requirements do exist. One such device is the Nordic Semiconductor Power Profiler Kit II [2], which was used to acquire the measurement data in the appendices 1 and 2. The Nordic Power Profiler and other similar devices utilize multiple shunt resistors of different values to widen the measurable current range [2].This is done by dynamically switching between resistors depending on the load current. The problem with the off the shelf devices is that they are quite expensive and hard to automate.

Automation was a major factor in the decision to create a custom solution for the current measurement. New software revisions were created frequently, which resulted in the need to automate the testing process as much as possible to save time. The measurement device was designed and included as a module on a larger test automation device that integrates the current measuring circuit and several other testing related modules onto a single Printed Circuit Board (PCB) controlled by a single microcontroller.

This thesis includes an explanation of the operating principle of the current measuring method, and how to apply the principle to create a working current measuring circuit. The physics of the measurement scheme are explained in chapter 2. All calculations and equations are based on common knowledge formulas in electronics. Chapter 3 describes how to apply the principle to create a working circuit for a given application, and what should be considered when selecting components for this type of circuit. Chapter 4 is dedicated to the measurement setup and results. The goal of the measurements was to find out how the measurement device performs at high dynamic ranges, by measuring both smaller and bigger currents. Another goal was to characterize how temperature affects the measurement results by measuring currents at a wide range of temperatures. In addition, different error sources and their effects on the measurement result were studied in chapter 5. Particularly interesting was how dielectric absorption influences the results. In chapter 6, the advantages and disadvantages of this measurement style is compared to traditional shunt resistor current meters. The ultimate purpose of this thesis is to give the reader enough knowledge to judge whether this type of current measurement is suitable for their application, and to be able to build a measurement device of their own.

2. THEORY OF OPERATION

The measurement method in question is based on discharging a large capacitor and measuring the time it takes for the capacitor's voltage to drop by a certain amount. In contrast to sampling measurement systems, where average current is obtained by averaging discrete measurements, this method measures the consumption continuously, essentially integrating instantaneous current measurements with an infinitely high sampling frequency. To understand how this works, it is necessary to first understand what electric current is, how it is defined and how capacitors behave in circuits.

2.1 Equations

Current is commonly measured and handled as instantaneous values, mathematically expressed as

$$I = \frac{\mathrm{d}q}{\mathrm{d}t}\ [3] \tag{1}$$

where dq is the number of charges moved during an infinitesimally small timestep dt. In this measurement method however, instantaneous current is less important than the average current over a longer time interval. Average current is mathematically defined similarly to instantaneous current as

$$I = \frac{\Delta q}{\Delta t}\ [3], \tag{2}$$

where Δq is a measurable change in charge and Δt is a measurable difference in time, instead of a time instant. This equation states that to know the average current, one must know the number of charges that have passed during the measured time. Time differences can be accurately measured with modern microcontrollers. The MCU used in this project has accurate built-in resonators and hardware counters to measure time accurately [4], which means accurate time measurement is relatively trivial to accomplish.

Change in charge on the other hand is not as trivial to measure, however, the definition of capacitance can be applied to equate a change in charge to a change in voltage, which is much easier to measure. The definition of a capacitance states that capacitance C is the ratio of charge q stored in a capacitor, to the voltage V of the capacitor. Mathematically this is expressed as

$$C = \frac{q}{V}\ [3]. \tag{3}$$

By re-arranging equation 3, charge can be presented as a function of capacitance and voltage as follows

$$q = CV. \tag{4}$$

Furthermore, if capacitance is assumed to be a constant quality of the capacitor component, a change in its charge can be expressed as a change in voltage between the terminals

$$\Delta q = C\Delta V. \tag{5}$$

Substituting Δq in equation 2 with equation 5, the following equation is acquired

$$I = C\frac{\Delta V}{\Delta t}. \tag{6}$$

Equation 6 now presents the average current as a function of capacitance, voltage difference and time difference. These are all quantities that are relatively easy to measure.

3. APPLYING THE PRINCIPLE

The voltage and time differences can be measured simultaneously by utilizing reference voltages and comparators. Two constant voltage references are required, both of which must be within the input voltage range of the Device Under Testing (DUT). In addition, there should be a measurable voltage difference between the references. One way to create these references is with resistors in voltage divider circuits, but in this case, Zener diodes were utilized.

Signals corresponding to the voltage reference levels can be generated by connecting one input terminal of a comparator to a reference voltage, and the other to the positive terminal of the current measuring capacitor. The comparators and references will be used to convert the analogue voltage value of the capacitor into two binary signals that can be read by a microcontroller. The comparator output will transition from high to low as the capacitor's voltage drops and reaches the respective reference voltage. The signal corresponding to the higher voltage will then be used to start a timer in software, which is then stopped by the signal from the lower voltage reference, as shown in Figure 1.

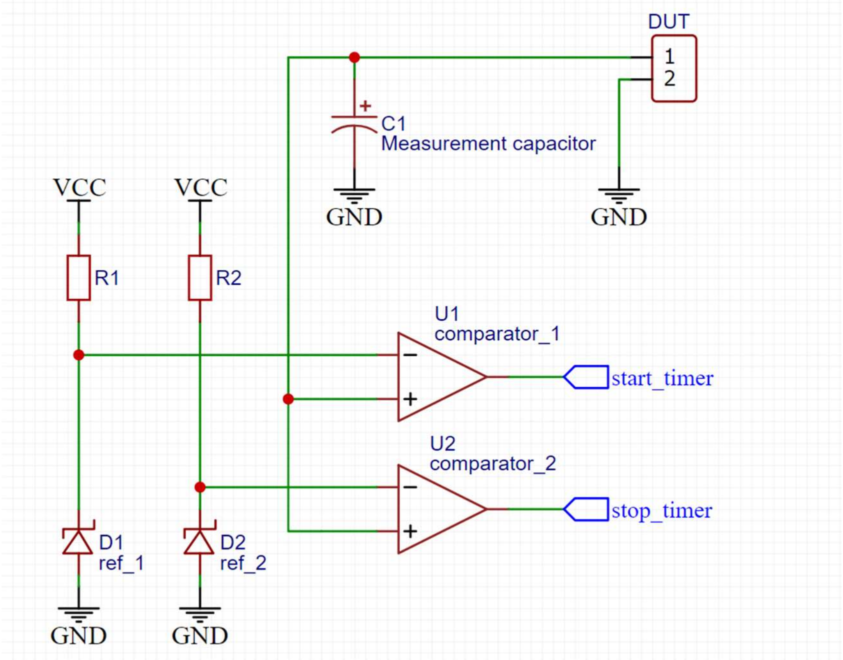


Figure 1. *Simplified diagram of the measurement circuit*

This circuit makes the voltage difference ΔV in the measurement a constant. Now $\Delta V = V_2 - V_1$, where the voltages V_2 and V_1 correspond to the Zener references connected to their respective comparators. Similarly, the time difference Δt will be expressed as $\Delta t = t_2 - t_1$. This will be the only variable in the measurements. These expanded values can now be substituted into equation 6 to get the equation

$$I = C\frac{V_2 - V_1}{t_2 - t_1} \tag{7}$$

where V_1 is the voltage corresponding to the start time t_1 and V_2 is the voltage corresponding to the stop time t_2. When implementing this equation in the microcontroller code, the voltage difference can be entered directly as a constant instead of subtracting the different voltages each time. The voltage difference should also be entered as a positive value, as the current reading would otherwise be negative, which would be true from the capacitor's perspective, but misleading when representing the current consumption of a device.

3.1 Connecting and disconnecting the capacitor

An aspect of the circuit that has not been discussed is how to charge the capacitor between measurements. This can be achieved in several ways, but perhaps it is best to use a relay. A relay has some advantages compared to transistors in this application, such as having near infinite resistance due to having an airgap between the terminals, where as a transistor will always have a galvanic connection between the switch contacts. The off resistance is of great importance in minimizing the effect of leakage currents on the measurement. If the switch connecting the capacitor and DUT to the power supply is leaky, it will feed some current to the circuit bypassing the capacitor, which will decrease the measurement result. Another possible concern is disconnecting the measurement capacitor from the DUT. If the DUT needs to be able to be powered off quickly, the measurement capacitor must be able to be disconnected from the DUT. If the capacitor is left connected and the power supply is disconnected, the DUT will still be powered for at least the designed measurement period, until the capacitor runs out of charge. A relay is again an easy solution. A circuit diagram implementing both of these switches is depicted in Figure 2. Moreover, if a certain type of relay, called dual pole dual throw relay, is used, both switch functions can be fulfilled with the same component, as illustrated in appendix 3.

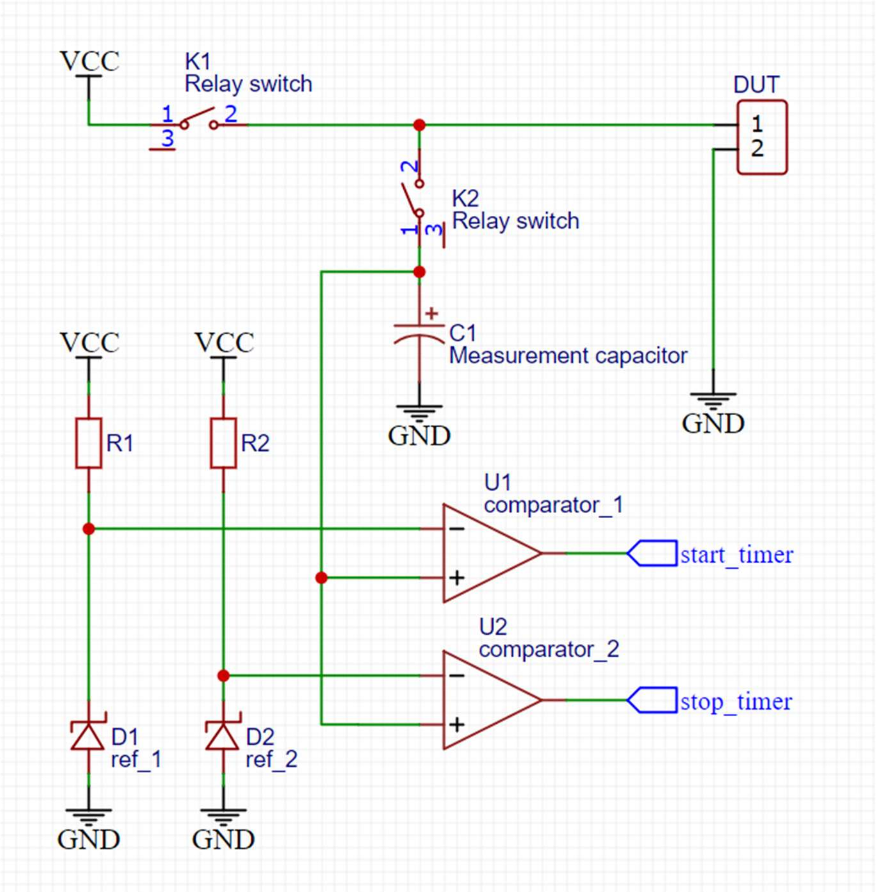


Figure 2. *Measurement circuit with relay switches and power connection*

An additional consideration is the in-rush current of the measurement capacitor. If the power supply providing the operating voltage VCC does not have a soft-start function, or the soft start is configured to be very fast, a current limiting resistor should be considered for the charging of the capacitor. For an easy example, let's say VCC = 5V, the power supply has a soft start feature with a rise time of 1ms. Let's also say that the capacitance is 1mF, which is a large capacitor, but not out of the question as explained in chapter 3.2.1. Previously, in the 2nd chapter, equation 6 was derived to calculate the average current while a capacitor is discharging, but this equation can also be utilized to calculate the charging current. Thus, by substituting the example numbers into equation 6, the average current during start-up will be

$$I = 1\text{mF}\frac{5\text{V}}{1\text{ms}} = 5\text{A},$$

which is very high and can cause the current limit on a power supply to activate and start dropping the output voltage. This can destabilize components in the rest of the connected system, especially microcontrollers, and cause un-wanted behaviour. A more complete circuit diagram that implements a current limiting resistor can be found in appendix 3.

3.2 Selecting components

When selecting components for the current measurement device, some properties should be examined carefully. Firstly, the leakage currents of all components connected to the positive terminal of the measurement capacitor should be as small as possible, including the capacitor itself. All leakages affect the measurement result directly, and contribute to decreased resolution and accuracy, since leakage currents are often hard to model accurately. If electrolytic capacitors must be used, a low leakage series should be considered. Nichicon offers at least one series of low leakage electrolytics [5].

Besides minimizing the leakages of individual components, another way to reduce leakage is to simply have less components connected to the measurement circuit. Even small leakages can add up to create significant error if there are enough of them connected in parallel. The designer should therefore seek to minimize the number of components connected to the positive terminal of the measurement capacitor.

3.2.1 Capacitor

The capacitor used to perform the current measurement should be sized so that the expected discharge time will be enough to average out the reading, especially if the current consumption of the DUT varies greatly with time. Usually around 10 to 60 seconds is enough, depending on the application. Equation 6 can be rearranged to calculate the capacitance needed for a given measurement time, voltage difference and current

$$C = I\frac{\Delta t}{\Delta V}. \tag{8}$$

The capacitor value should almost always be rounded up heavily as it is better in most cases to measure for a longer period rather than a shorter period. This prioritizes the dynamic range for higher currents at the cost of dynamic range for lower currents. If current values are expected to lower in the future, the capacitance could be rounded down to prepare for lower current measurements. The dynamic range will be discussed further in chapters 4 and 5.

In many designs the required capacitance value will be quite high, especially if the expected currents are higher, or the measurement time needs to be long, the required capacitances can reach into the millifarads. The capacitor voltage rating should be selected so that the operating voltage is no more than 40% of the capacitor’s rated maximum in order to reduce leakage [7]. Utilizing multiple capacitors in series can help reduce the required voltage rating of the individual capacitor, but the designer needs to keep in mind that the voltage doesn't necessarily divide evenly between the capacitors [7]. Furthermore, connecting capacitors in series has the added benefit of decreasing the leakage further by adding up the equivalent series resistances of the capacitors [7].

If the required capacitance can be achieved with plastic or ceramic capacitors they should be utilized, however, the high capacitance requirements mean that electrolytic capacitors are in many cases the only viable option, due to their higher energy density. If PCB space is not limited, plastic or ceramic capacitors could be used by connecting them in large parallel and series banks to avoid using electrolytics. Electrolytic capacitors cause some issues, including a phenomenon called dielectric absorption [8], which will be discussed further in chapter 5.

3.2.2 Comparator and voltage references

The comparator used for triggering the timer events should have the following qualities: low input leakages, and a rail-to-rail input voltage range. The rail-to-rail input is important if the comparator is powered by the same source as the measurement circuit. Rail-to-rail operation means that the comparator's input signals can reach voltage levels that are very close to the comparator's supply voltages. For example, 0.3 V [9] lower than the positive supply and 0.3V higher than the negative, often ground. Normal comparators, on the other hand, can require a difference of 1.5V or more [10] to the supply voltage. This can limit the selected voltage references and require the capacitor voltage to be dropped lower than otherwise necessary. If the comparator is powered from another, higher voltage, source then this is not as much of a concern.

When selecting reference voltages, the designer should be careful to respect the operating voltage range of the Device Under Testing. The upper reference should be at least below the ripple level of the supply voltage, but the comparator's properties should also be considered as discussed previously. The lower limit is determined by the DUT, as it must remain operational during the whole measurement cycle. If the DUT power must remain uninterrupted, the lower limit should also include some buffer for the relay switching time, as the voltage may drop while the relay contact is swinging from pole to pole, and the DUT is essentially disconnected from all power sources for a short period. This is an aspect where using a solid state relay or switch would be advantageous for their speed.

The start and stop references should also be separated by enough voltage so that even in the worst tolerance cases, there is still a big enough difference in the references that voltage ripple is not a significant factor. The tolerances of the references can be calibrated for, as described in chapter 3.4. Another issue with having a very small difference between the references is that a greater capacitance will be needed to achieve the same measurement period as with a bigger voltage difference.

The measurement circuit can incorporate more than just two voltage references to create multiple voltage levels for measurement. Multiple voltages may be desirable for example for measuring the current consumption of different devices that have different operating voltage ranges. The disadvantage is that the capacitors will need to be rated according to the highest voltage level.

3.3 PCB design considerations

The measurement circuit has no fast signals and doesn’t require small components. As a result, the design is quite lenient in terms of PCB manufacturing process and design rules. The only rule that should be followed is to keep the capacitor voltage measurement line, the conductor connecting the comparators to the capacitor, clear of interference. This helps the timing be as consistent as possible, as sudden changes in the measured voltage could trigger the comparator earlier or later than intended. A small ceramic filtering capacitor should be considered, as their leakage currents are extremely small, so it is unlikely to affect the measurement result.

The footprint of this circuit is quite large, as it includes a relay and possibly some large capacitors. The required area and height vary greatly as a function of the required capacitance and maximum voltage. Usually, for a given size of capacitor, the product of its capacitance and maximum rated voltage is constant. This means that if either of the values needs to be increased, the size of the capacitor will also need to be larger. As shown by equation 7, the capacitance requirement increases linearly to the expected current. Therefore, it is likely that for high current applications, 10s of milliamps or more, this method may not be the best solution, as the required space for the capacitors will be quite large.

3.4 Calibration

Capacitors are often not the most precise components in terms of their actual capacitance [7]. For instance, the capacitance of electrolytic capacitors is usually guaranteed to only around ±20% of the rated value [5]. Consequently, a calibration step must be done before any measurements to obtain the true capacitance value of the measurement capacitor. One way to achieve this is by substituting the DUT with a constant current load, measuring the discharge time, and calculating the capacitance with equation 8. Accurate constant current loads might be hard to find, whereas accurate resistors are cheap and plentiful. The capacitance can be measured from a known resistance by applying the well-known formula for a capacitor discharging through a resistor. The formula describes the voltage of a capacitor as a function of time

$$V_t = V_0 e^{-\frac{t}{RC}}\ [3]. \tag{9}$$

In this case, the initial voltage V_0 will be substituted by the start voltage V_1 and voltage V_t will be substituted by the stopping voltage V_2 as follows

$$V_2 = V_1 e^{-\frac{t}{RC}} \tag{10}$$

From this equation, it is possible to solve for capacitance

$$C = \frac{-t}{R \times \ln\left(\frac{V_2}{V_1}\right)}. \tag{11}$$

Equation 11 essentially allows for measuring the capacitance of the measurement capacitor with the existing circuit, the only new component being a single resistor. The resistor can even be an inaccurate one if the resistance can be measured accurately before the calibration. The calibration procedure also accounts for any inaccuracies in the reference voltages, and includes their error in the calculated capacitance value, so that during actual measurements, the reference voltages can be addressed with their nominal values. This is especially useful when implementing this into the microcontroller code, as the natural logarithm may be a heavy operation to do, especially if there is no Floating-Point Unit (FPU) available. By having the reference values constant in the code, the natural logarithm is also a constant and can be calculated beforehand. The result of the calibration should be saved in non-volatile memory, such as Flash memory, to avoid having to re-do the calibration every time the measurement device is powered off.

For best results, the calibration resistor should be sized so that the average current during calibration matches the expected average current during real measurements as closely as possible. A good estimate for the resistor value can be calculated by taking the average of the start and stop voltages

$$V_{avg} \approx \frac{V_1 + V_2}{2}, \tag{12}$$

and using Ohm's law $U = RI$ [3] to calculate the needed resistance from the average voltage and the expected average current. This can be done by substituting the average voltage, and re-arranging Ohm's law to solve for resistance

$$R = \frac{V_{avg}}{I}. \tag{13}$$

V_{avg} can be substituted with equation 12 to directly calculate the resistance from the references and the expected average current with the equation

$$R \approx \frac{V_1 + V_2}{2\,I}. \tag{14}$$

3.5 Example

In this chapter a hypothetical device is studied for the purpose of illustrating the usage of the formulas given in chapters 2 and 3. The hypothetical device will be referred to as the DUT.

The DUT is rated to work at a range of 5-3.3 V and is expected to consume on average 20 uA of current. Good reference voltages would in this case be 4.7V and 3.6V, since they fit within the operating range, and can be easily created with Zener diodes [6]. This will result in a ΔV of 4.7-3.6V = 1.1V. Let's also say that the DUT is running in a fast loop, with no cyclical operations longer than a couple seconds, so the measurement period will be targeted at 10 s to include multiple operating cycles into the measurement. Placing these into equation 8, gives us the required capacitance

$$C = 20\ \mu\text{A}\frac{10\ \text{s}}{1.1\ \text{V}} \approx 182\ \mu\text{F}.$$

Once the circuit is built, it needs to be calibrated. A suitable resistor for calibration can be found by approximating the average voltage with equation 12

$$V_{avg} \approx \frac{4.7\ \text{V} + 3.6\ \text{V}}{2} \approx 4.15\ \text{V},$$

and applying the variation of Ohm's law in equation 13

$$R = \frac{4.15\ \text{V}}{20\ \mu\text{A}} \approx 200\ \text{k}\Omega.$$

4. MEASUREMENTS

All tests were run with a measurement circuit with four 2.2 mF Nichicon capacitors rated at 6.3 V maximum. The capacitor bank was configured in a 2 x 2 configuration, meaning two parallel sets of two capacitors in series for a total of 2.2 mF of capacitance. This helped raise the theoretical maximum voltage to over twice the operating voltage of the circuit, which was 6 V. The DUT was expected to consume an average of 50 µA, and the measurement period was targeted at 40 seconds. The voltage references used were 5.6 V and 4.7 V creating a voltage difference of 0.9 V. The time measurement was implemented in software instead of a hardware timer, resulting in a timing resolution of 2 ms. All measurement devices were calibrated with a 100 kΩ resistor, equating to around 51 µA of current consumption. The calibration was started around 10 minutes after powering on the circuit, however, this was not tightly controlled.

Four unique measurement devices were used in gathering the data. These devices were given identifying numbers from 17 through 20, based on their serial COM port numbers. A total of 12 resistors were used as simulated loads in the measurements. The resistors, their nominal values and actual values are presented in table 1.

Table 1. *Load resistors*

Nominal value (Ω)	Measured value (Ω)
5.1k	5089.8
10k	9970.2
33k	32989
47k	46959
51k	50789
100k	99768
330k	329550
470k	473270
510k	511410
1M	1003200
5.6M	5598300

The resistances were measured with a calibrated Keysight 34465A digital multimeter with 6.5 digits of precision [11]. Some of the digits were discarded due to measurement variation. The results were rounded to the last stable digit.

A problem with using resistors as the load is that their current consumption is dependent on the voltage, which is constantly changing. This means that calculating what the result of the current measurements should ideally be is not trivial and requires a new equation to calculate accurately. The required equation can be derived by combining the measurement equation 6

$$I = C\frac{\Delta V}{\Delta t}$$

with the calibration equation 11

$$C = \frac{-\Delta t}{R \times \ln\left(\frac{V_2}{1}\right)}.$$

The capacitance in equation 6 can be substituted with equation 9 to find an equation for current

$$I = \frac{-\Delta t}{R \times \ln\left(\frac{V_2}{V_1}\right)} \frac{\Delta V}{\Delta t}. \tag{15}$$

As can be seen, the equation can be further simplified by reducing the time deltas, which results in the final equation

$$I = \frac{-\Delta V}{R \times \ln\left(\frac{V_2}{V_1}\right)}. \tag{16}$$

This equation allows us to calculate the ideal current value that the measurement device should produce for any resistance. This equation was applied to the measured resistances in Table 1 to calculate the current values in Table 2.

Table 2. *Resistors and their corresponding current values*

Resistor (Ω)	Calculated ideal current (µA)
5.1k	1009.2
10k	515.22
33k	155.71
47k	109.39
51k	101.14
100k	51.488
330k	15.588
470k	10.854
510k	10.045
1M	5.1205
5.6M	0.9176

4.1 Dielectric absorption

Dielectric absorption is the name of the effect where a capacitor does not immediately release all of the charge stored in it when discharged. The effect is particularly noticeable in electrolytic capacitors. This can be observed by quickly discharging a capacitor to zero, disconnecting it from any circuits, and measuring its voltage several minutes after disconnecting it. The voltage should have risen above zero, as if the capacitor charged itself. [8]

This effect also affects the charging of a capacitor. A capacitor does not fully charge immediately after being connected. It may take several minutes for the final charge to soak in via dielectric absorption. This is why it is important to let the measurement capacitors rest at the operating voltage for some time before starting any measurements, to minimize, or at least standardize, the effects of dielectric absorption.

Dielectric absorption is studied by turning on the circuit and letting the capacitor rest at the operating voltage for different amounts of time before starting each measurement. The power is turned off for 10 minutes between every measurement cycle. Table 3 depicts current measurements at seven different current levels from around 500 µA to 10 µA. The circuit was let rest for 10 seconds before the measurement. In 0, the same measurements were performed, with the difference that the devices were allowed to rest for 100 seconds. In Table 5 and Table 6 the rest times were 500 and 900 seconds respectively.

Every measurement was performed with all four devices and their results were combined into an average result. A sample standard deviation was calculated from the different devices' results using Microsoft Excel's STDEV.S() function. The measurement error and the standard deviation was then normalized by dividing them with the ideal current value calculated with equation 13. This results in error and deviation values in percentages that can be compared between different measurements regardless of the current level.

Table 3. *10 second rest time*

Ideal (µA)	Average result (µA)	Error (%)	Deviation (%)
515.2	534.00	3.95	0.40
155.7	162.00	4.04	0.00
109.4	113.75	3.99	0.44
51.49	54.04	4.96	0.22
15.59	16.29	4.51	0.32
10.85	11.30	4.11	0.59
10.04	10.45	4.02	0.44

Table 4. *100 second rest time*

Ideal (µA)	Average result (µA)	Error (%)	Deviation (%)
515.2	534	2.59	0.41
155.7	162	0.66	0.32
109.4	113.75	0.33	0.46
51.49	54.0395	0.96	0.21
15.59	16.29025	1.18	0.29
10.85	11.3	1.23	0.41
10.04	10.448	1.24	0.40

Table 5. *500 second rest time*

Ideal (µA)	Average result (µA)	Error (%)	Deviation (%)
515.2	526.25	2.45	0.42
155.7	156.25	0.34	0.32
109.4	109.25	-0.13	0.46
51.49	51.37	-0.22	0.23
15.59	15.45	-0.89	0.33
10.85	10.75	-0.98	0.44
10.04	9.94	-1.00	0.35

Table 6. *900 second rest time*

Ideal (µA)	Average result (µA)	Error (%)	Deviation (%)
515.2	526.25	2.45	0.39
155.7	156.50	0.50	0.37
109.4	109.00	-0.36	0.75
51.49	51.28	-0.40	0.19
15.59	15.38	-1.35	0.37
10.85	10.69	-1.52	0.48
10.04	9.89	-1.55	0.34

The following figures from Figure 3 to Figure 6 depict the data from the above tables in a more visual and easier to read format.

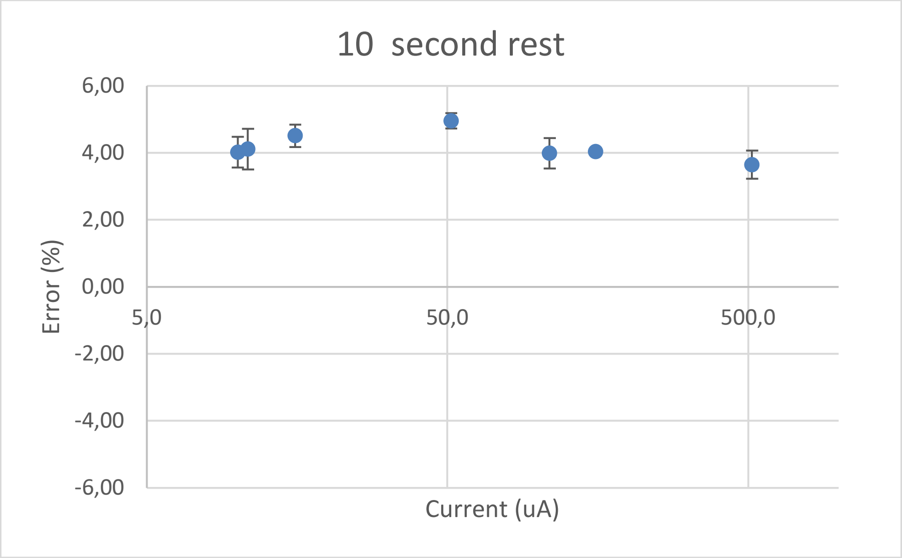


Figure 3. *Measurement error as a function of current, 10 s rest*

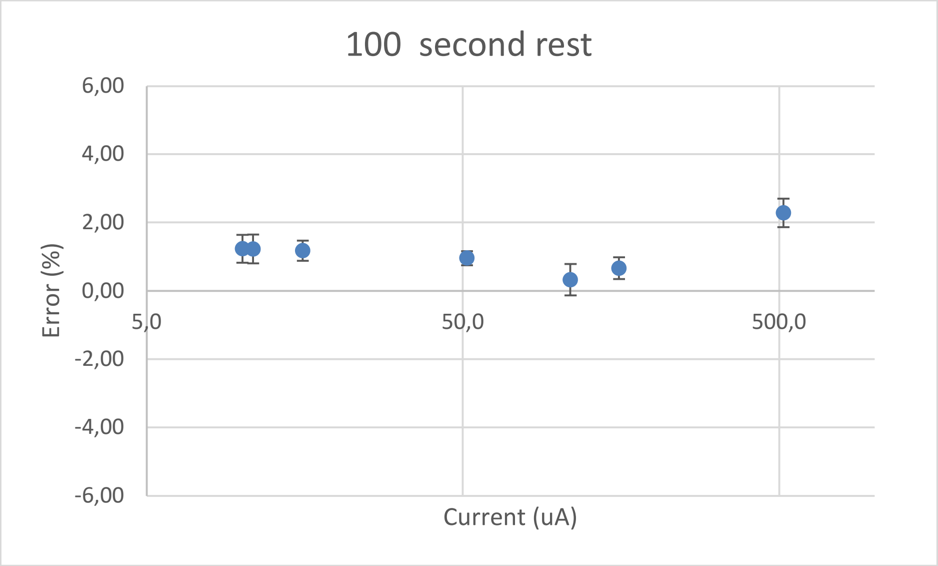


Figure 4. *Measurement error as a function of current, 100 s rest*

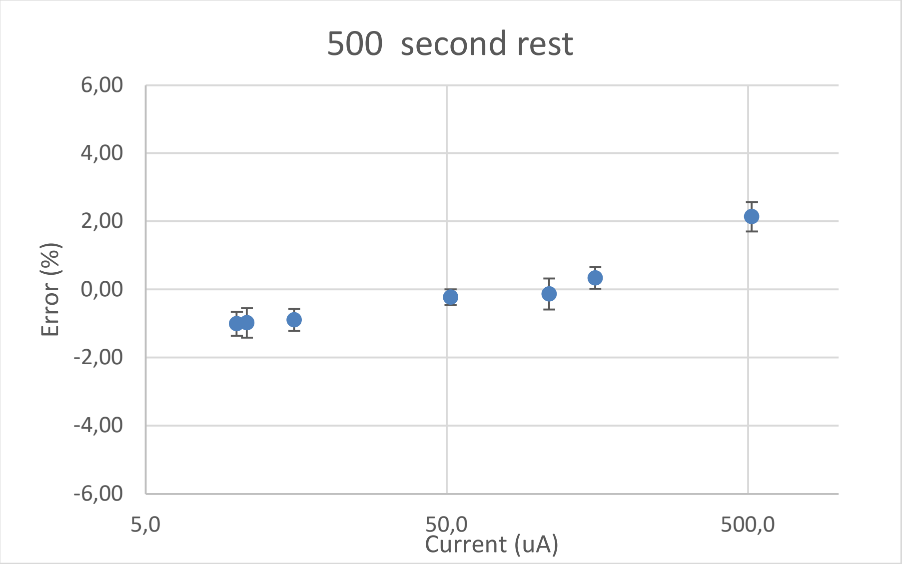


Figure 5. *Measurement error as a function of current, 500 s rest*

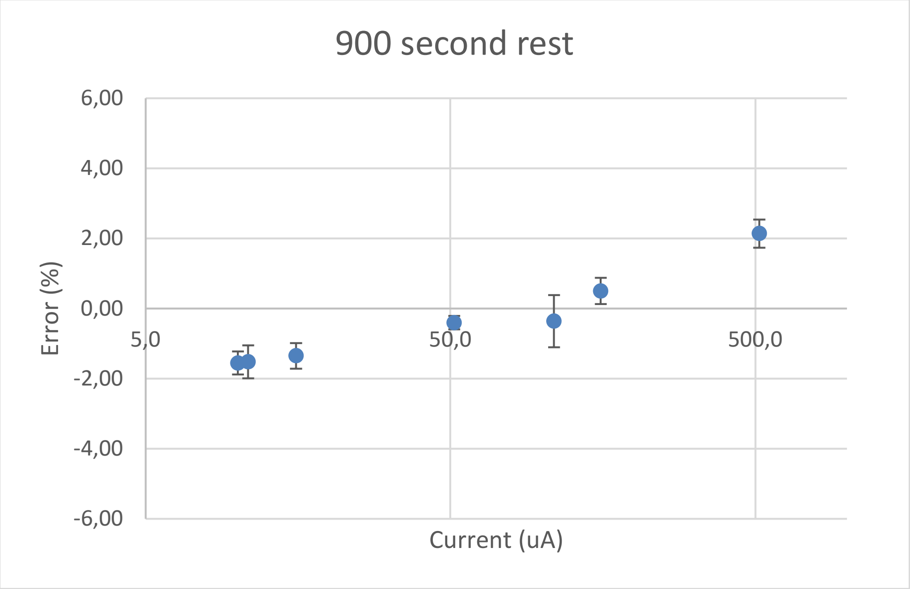


Figure 6. *Measurement error as a function of current, 900 s rest*

The following data represents only one device, so standard deviation is not displayed. This measurement series tested the effect of having the circuit unpowered for a longer period between each measurement, and the effects of dielectric absorption. The circuit was powered off for 10 hours between measurements. This series also measured higher and lower currents than in the previous measurements. Table 7 presents the results of these measurements.

Table 7. *High dynamic range tests, 10h breaks between measurements*

Calculated current (µA)	**Measured currents (µA)**				
	0 s	60 s	5 min	10 min	10 h
0.917	1.161	0.99	0.956	0.941	0.879
10.072	11.69	10.54	10.13	10	9.84
100.723	111.1	102.6	101.2	101.1	101
1007.229	1095	1044	1043	1043	1044

Next, the measurement error was calculated as a percentage of the calculated ideal current value using the same methods as . The calculated errors are presented in Table 8 and Figure 7.

Table 8. *Error results of high dynamic range tests*

Calculated current (µA)	**Measurement error (%)**				
	0 s	60 s	5 min	10 min	10 h
0.917	26.57	7.93	4.22	2.58	-4.18
10.072	16.06	4.64	0.57	-0.72	-2.31
100.723	10.30	1.86	0.47	0.37	0.28
1007.229	8.71	3.65	3.55	3.55	3.65

Figure 7. *Data from Table 8 presented as a figure*

4.2 Temperature coefficient

To find out the temperature behaviour of the circuit, current measurements were performed at a temperature range of -20C to 60C. The measurements were performed at 10 °C intervals. Each temperature was held for at least one hour to let the temperature stabilize. The measurements were performed on all four devices, at four different current levels to confirm that the temperature behaviour is the same regardless of the amplitude of current. For conciseness, only the average results are presented in Table 9, the raw data can be found in appendix 5.

Table 9. *Average results for each temperature and each load*

Temperature (°C)	10 kΩ resistor average (µA)	51 kΩ results average (µA)	100 kΩ results average (µA)	510 kΩ results average (µA)
-20	613,3	117,8	59,37	11,31
-10	592,0	113,6	57,27	10,93
0	571,5	109,7	55,36	10,58
10	551,7	106,1	53,57	10,27
20	533,3	102,8	51,91	9,97
30	516,5	99,6	50,34	9,68
40	501,1	96,7	48,84	9,39
50	486,3	93,8	47,37	9,07
60	472,0	90,9	45,80	8,68

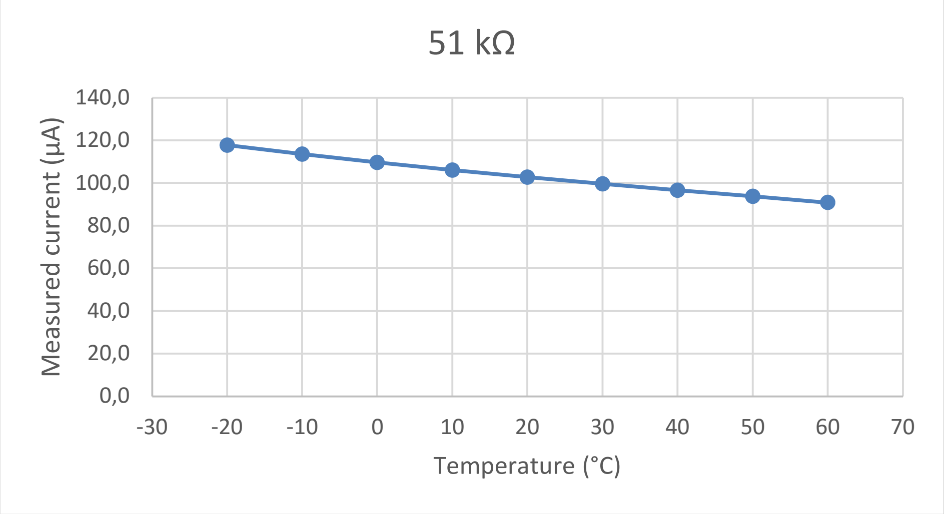


Figure 8. *Third column of Table 9 as a figure*

Figure 8 illustrates the linearity of the results from the temperature coefficient measurements. Table 10 contains the same measurement data organized differently. Instead of averaging the results for each temperature, the coefficient was first calculated for each device to determine the variance between them and calculate an average for each current level. Table 11 contains an average of these averages to represent an approximate coefficient for all current levels. The deviation in Table 11 was calculated from all the coefficients in Table 10.

Table 10. *Temperature coefficients per device and on average with error margins*

Device	**10 kΩ load (%/°C)**	**51 kΩ load (%/°C)**	**100 kΩ load (%/°C)**	**510 kΩ load (%/°C)**
17	-0,349	-0,336	-0,332	-0,323
18	-0,338	-0,327	-0,320	-0,309
19	-0,346	-0,330	-0,324	-0,315
20	-0,341	-0,330	-0,325	-0,315
Average	**-0,343 ±0,0048**	**-0,331 ±0,0038**	**-0,325 ±0,0048**	**-0,315 ±0,0057**

Table 11. *Average of the averages for each load*

Temperature coefficient	**Standard deviation**
-0,329 %/°C	± 0,011 %/°C

The results are displayed in percentages, however, when using the coefficient to correct for temperature effects, the true value of -0,00329 should be used, as the percentage number would apply the correction 100 times greater than the actual value.

5. ERROR STUDY

Firstly, some key terms need to be defined. Accuracy describes how closely the measurement result matches the ideal value; this is obviously an important aspect of a measurement device. Another important aspect is precision, which describes the repeatability of the measurement. In simple terms, how closely do repeated measurements match each other.

When the conditions and load remained the same, the precision of the results was extremely high. At first, measurements were performed multiple times. The precision within a single measurement device was always at least three digits. This is why the raw data in appendices 4 and 5 contains only one measurement point for each different measurement per device. The variation would have been negligeable, and the amount of data would have been overwhelming, had multiple measurements been included for each data point. The accuracy of the results varied with the current level. The most accurate results were unsurprisingly obtained when measuring at the calibration conditions, which were a current of around 50 µA, and a rest time of 500 seconds, or close to 10 minutes. Measuring from the calibration point up to 10 times higher and 10 times lower, the accuracy stays within 3 %. Going below 1 µA or above 1 mA the accuracy starts to drop off and the error climbs closer to percent.

The measurements were performed over several months and no drift was observed during this time. Nevertheless, if the current meter is suspected to have drifted, or be inaccurate, it can always be recalibrated at the expected current level to regain confidence in the measurements.

At higher currents, the positive measurement error seen in figures 3 to 7 could be from limitations in time measurement resolution. Modifying equation 6 to solve for measurement time Δt gives the equation

$$\Delta t = C\frac{\Delta V}{I}. \tag{17}$$

Using this equation, the measurement time when measuring a current of 1 mA would be

$$2.2\ \mathrm{mF}\frac{0.9\ \mathrm{V}}{1\ \mathrm{mA}} \approx 1.9\ \mathrm{s},$$

which is quite short, but the time resolution of 2 ms is only 0.1 % of that, so not all the error can be attributed to timing error. The error could be from dielectric absorption, meaning that the capacitor is discharged so quickly that it doesn’t have time to release all the charge inside it, which causes the voltage to drop faster than normally, which results in a higher calculated current.

Dielectric absorption has a much greater impact on the measurement precision for smaller currents, as can be seen in Figure 7. This makes sense since dielectric absorption is an effect that happens slowly over time. As the 10-hour graph in Figure 7 illustrates, having the capacitors be charged up for a longer time increases their actual capacitance, which increases the discharge time, which results in a smaller measured current, but only if the capacitors are discharged slowly with a very small current. This way the soaked-up charges have time to release from the dielectric material of the capacitor.

Temperature changes affect the measurement result significantly, but predictably, as seen in Table 10. The variation between devices was very small, however, device 18 differed from the rest slightly. A temperature dependence was found, and the coefficient varied slightly with the measured current. At higher currents, the coefficient was -0,343 ±0,0048 %/°C, and at lower currents -0,315 ±0,0057 %/°C. The temperature dependence is most likely due to the electrolytic capacitor as the other components that could affect the result have quite small temperature dependences. The used load resistors had a coefficient of 50ppm/°C, which is negligeable, and the reference voltages have coefficients of 0.038%/°C and ±0.030%/°C [6], which are more significant, but still only around a 10th of what was observed. The capacitor datasheet does not specify a temperature coefficient, but it is safe to assume that electrolytic capacitors, which have liquid inside them are affected by temperature changes.

If an accurate reading needs to be achieved at different temperatures, a corrective calculation needs to be performed to account for the temperature coefficient. One way to perform the compensation is to use the equation

$$I = I_{meas} * \left(1 + \alpha * (T_{cal} - T_{meas})\right), \tag{18}$$

Where I_{meas} is the measured current, T_{meas} is the temperature during the measurement, T_{cal} is the temperature at which the device was calibrated, and α is the temperature coefficient.

6. CONCLUSIONS

This method does not replace sampling current meters like the earlier mentioned Nordic Power Profiler, especially for visualizing the power consumption profile as a function of time. The long measurement period does however hide the short-term current draw fluctuations, essentially performing a continuous integration that perfectly captures even the fastest changes in current consumption. In this regard, the design fulfils the goals set in the design phase, and as a microcontroller-based system, the data can be output in a format that suits any test automation script.

This method provides quite accurate results with a high resolution, given that the conditions are controlled, especially the on and off time of the circuit before the measurement. This measurement scheme can measure a wide range of currents at the cost of significant changes in the measurement period. As the equations suggest, the measurement period is inversely proportional to the average current draw. This means that a doubling of the current will halve the measurement time, which may or may not be a problem, depending on the application.

Another advantage when comparing to shunt resistor current meters is the ability to have the ground reference of the DUT connected directly to the measurement device. And any other connected devices. In sampling current meters, the shunt resistor is on the low side of the circuit, meaning that if the ground of the DUT is connected to the ground of the measurement device, the shunt resistor is essentially shorted. Having the grounds separated by the shunt resistor is usually not a problem, as the voltage difference is quite small, but there are cases where it might be advantageous to have a common ground between all the devices.

The biggest disadvantages are due to the dielectric absorption, which imposes timing limits on the measurements to produce accurate and precise results. This could possibly be alleviated by using a capacitor type with better parasitic properties. Ceramic and plastic capacitors exhibit much less dielectric absorption than electrolytic ones [8], but they are more limited in terms of capacitance, which means that higher currents and long measurement times are impractical to achieve. For even higher currents than studied here, the capacitance would have to be even greater, which would increase the size of the circuit, making the device less practical.

Another possible disadvantage is the non-constant voltage during the measurement. If the power input of the DUT is unregulated, the changing voltage might affect the result. Sampling current meters also inherently affect the voltage, although often the effect is smaller. Besides the larger voltage fluctuations during measurement, another challenge is the quite limited voltage range due to the capacitors’ maximum voltage rating. The measurement circuit needs to be tailored for the device under testing making the circuit less universal, and therefore unlikely to have off the shelf designs available even if this measurement method was widely used.

A very interesting follow up study would be to create a measurement circuit optimized for 1 μA and smaller currents, using only ceramic or plastic capacitors, and measure the performance. Based on the discussed capacitor properties, a hypothesis could be made that a circuit utilizing ceramic or plastic capacitors with better parasitic properties would be even more accurate. This would of course need to be verified by building the circuit and measuring the performance.

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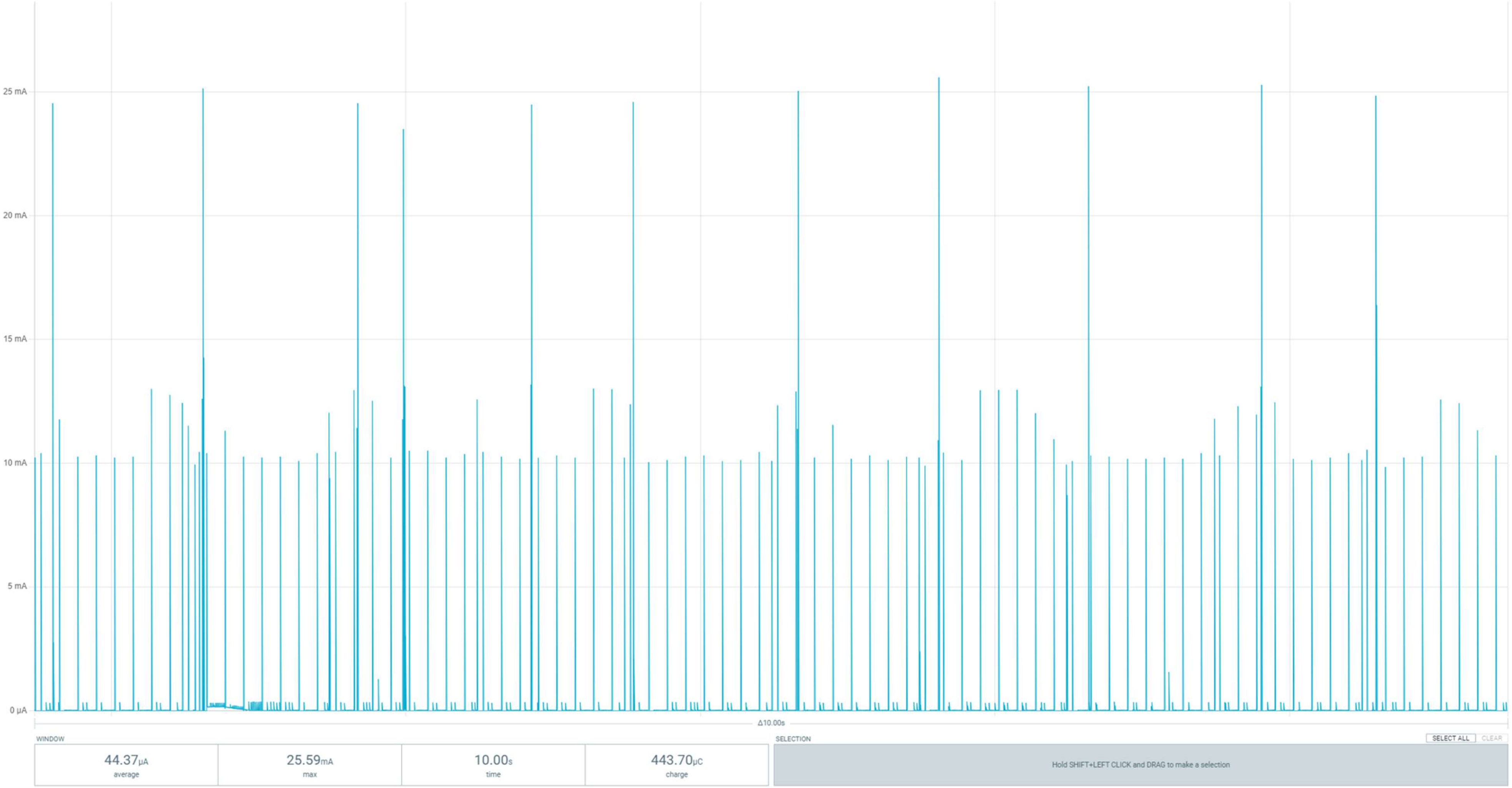
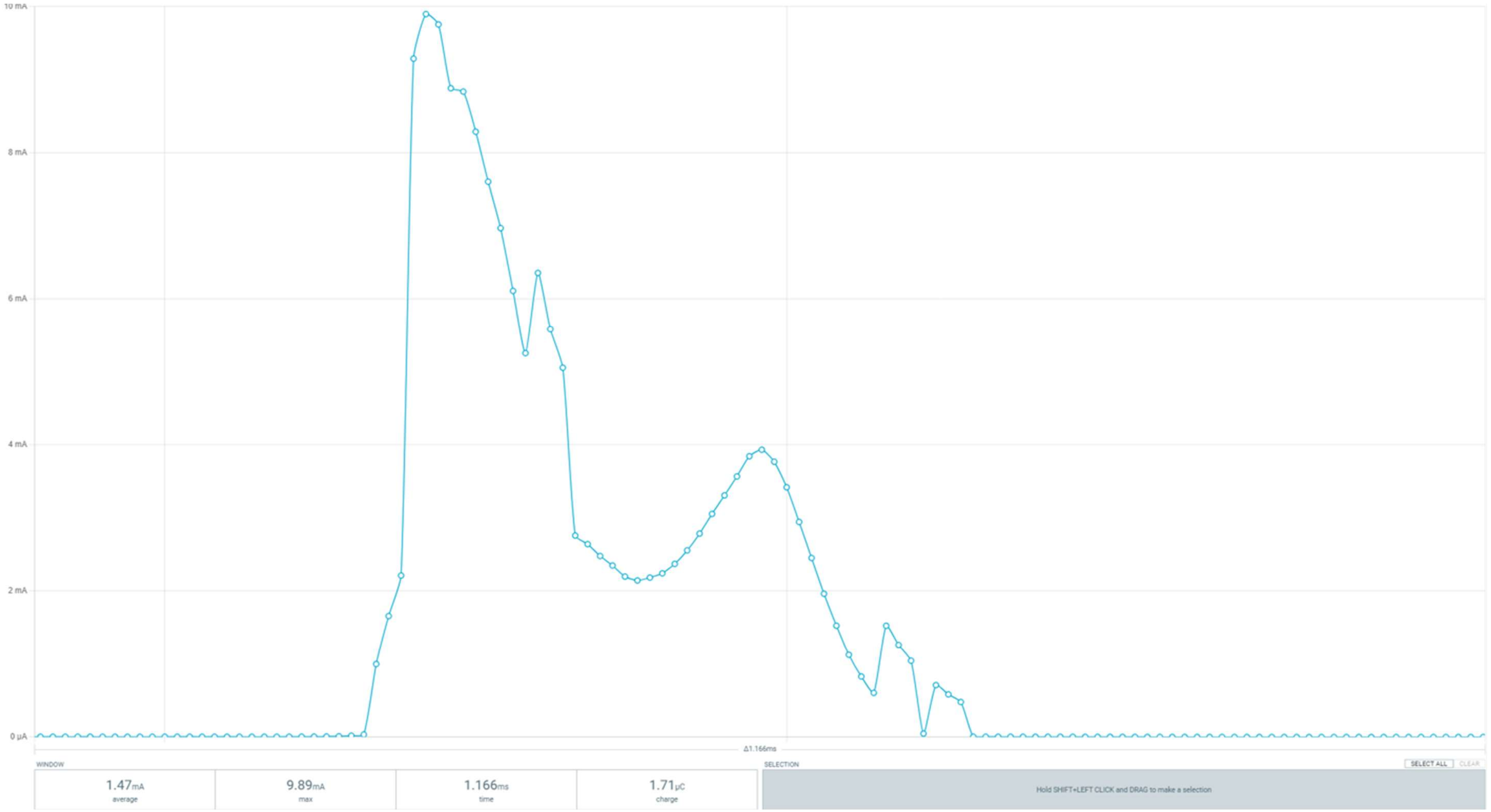
APPENDIX 1: SAMPLING NORDIC POWERPROFILER II MEASUREMENT



44.37µA average	25.59mA max	10.00s time	443.70µC charge

Hold SHIFT+LEFT CLICK and DRAG to make a selection

APPENDIX 2: ZOOMED IN ON ONE OF THE MEASURED PEAKS



WINDOW

1.47mA average

9.89mA max

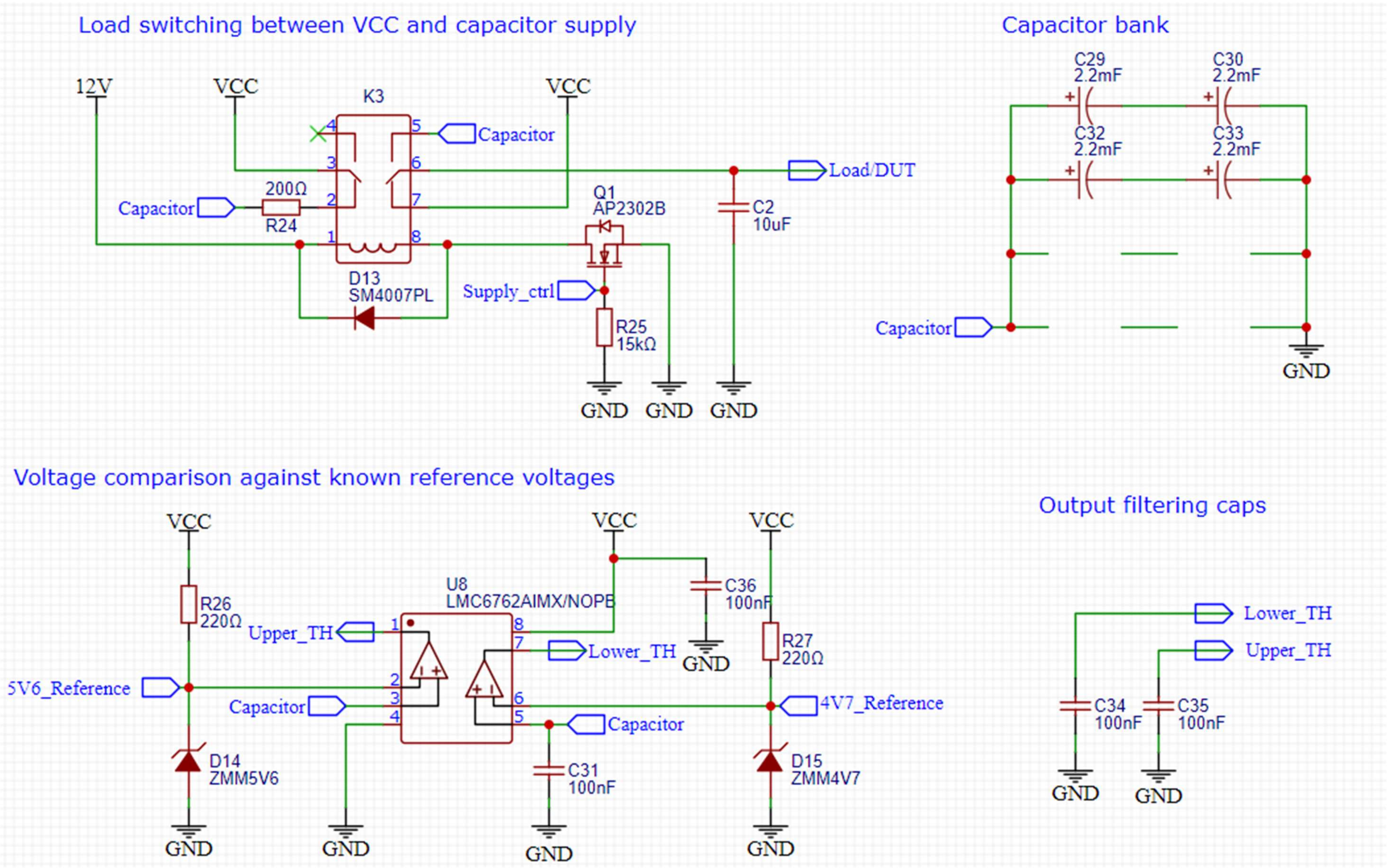
1.166ms time

1.71µC charge

SELECTION

Hold SHIFT+LEFT CLICK and DRAG to make a selection

APPENDIX 3: MEASUREMENT CIRCUIT DIAGRAM



APPENDIX 4: DIELECTRIC ABSORPTION MESUREMENTS IN MICRO AMPERES

Device id	17	18	19	20		17	18	19	20		17	18	19	20		17	18	19	20
resistance (Ω)	99768					329550					473270					511410			
Rest time (s)																			
0	56.30	56.23	56.66	56.63		16.83	17.10	17.09	16.84		11.65	11.63	12.02	11.70		10.81	10.75	10.95	10.99
1	55.40	55.28	55.63	55.69		16.60	16.66	16.73	16.63		11.47	11.46	11.69	11.54		10.63	10.58	10.72	10.72
3	54.90	54.69	55.00	55.06		16.46	16.47	16.56	16.48		11.38	11.36	11.54	11.43		10.53	10.49	10.60	10.61
5	54.59	54.34	54.64	54.70		16.38	16.38	16.47	16.40		11.33	11.31	11.47	11.39		10.50	10.44	10.55	10.56
7	54.38	54.13	54.39	54.46		16.32	16.33	16.43	16.35		11.30	11.27	11.42	11.37		10.48	10.41	10.52	10.52
9	54.19	53.96	54.17	54.23		16.27	16.28	16.38	16.31		11.27	11.24	11.39	11.34		10.46	10.39	10.49	10.50
10	54.10	53.87	54.06	54.13		16.25	16.26	16.37	16.29		11.27	11.23	11.37	11.34		10.45	10.38	10.47	10.49
30	53.15	52.88	53.02	53.12		16.04	16.04	16.14	16.08		11.15	11.10	11.23	11.21		10.35	10.27	10.34	10.37
50	52.67	52.41	52.53	52.62		15.92	15.91	16.01	15.95		11.07	11.02	11.14	11.14		10.28	10.20	10.27	10.30
70	52.38	52.13	52.24	52.33		15.83	15.82	15.92	15.86		11.02	10.97	11.08	11.09		10.24	10.15	10.22	10.25
90	52.19	51.93	52.02	52.11		15.77	15.75	15.85	15.80		10.99	10.93	11.03	11.04		10.20	10.12	10.19	10.21
100	52.11	51.85	51.95	52.02		15.76	15.71	15.82	15.79		10.98	10.93	11.01	11.03		10.19	10.11	10.18	10.20
300	51.57	51.33	51.45	51.55		15.54	15.47	15.58	15.56		10.82	10.76	10.83	10.86		10.04	9.96	10.01	10.04
500	51.44	51.21	51.37	51.48		15.45	15.38	15.49	15.48		10.76	10.68	10.76	10.79		9.97	9.90	9.94	9.97
700	51.38	51.16	51.35	51.39		15.39	15.33	15.45	15.45		10.73	10.64	10.72	10.76		9.94	9.87	9.90	9.93
900	51.33	51.14	51.35	51.31		15.36	15.31	15.43	15.42		10.71	10.62	10.70	10.73		9.92	9.85	9.88	9.91

Device id	17	18	19	20		17	18	19	20		17	18	19	20		17	18	19	20
Resistance(Ω)	9970.2					32989					46959					99768			
Rest time (s)																these	values	not	used
0	564	561	563	565		172	168	174	172		120	121	123	120		57	56	57	56
1	551	551	551	555		168	166	169	169		118	117	119	118		55	55	55	55
2	547	547	547	550		166	166	168	167		117	116	118	117		55	54	55	55
3	545	543	544	547		166	165	166	166		116	116	117	116		55	54	55	55
4	542	540	540	544		165	164	165	165		116	115	116	116		54	54	54	54
5	541	539	539	542		164	164	165	165		115	115	116	116		54	54	54	54
6	539	536	537	540		164	163	164	164		115	114	115	115		54	54	54	54
7	538	535	535	539		163	163	163	164		115	114	115	115		54	54	54	54
8	537	533	535	538		163	162	163	163		115	114	115	115		54	53	54	54
9	537	532	534	536		163	162	162	163		114	113	114	115		54	53	54	54
10	535	531	534	536		162	162	162	162		114	113	114	114		54	53	54	54
20	532	528	530	533		160	160	160	160		113	112	113	113		53	53	53	53
30	530	526	529	531		159	159	159	159		112	111	112	112		53	52	53	53
40	530	526	528	531		159	158	159	159		111	111	111	112		52	52	52	52
50	530	526	528	530		158	158	158	158		111	110	111	111		52	52	52	52
60	529	526	527	530		158	157	158	158		111	110	111	111		52	52	52	52
70	529	524	528	530		158	157	158	158		111	110	110	111		52	52	52	52
80	528	524	528	529		158	157	158	158		110	110	110	111		52	51	52	52
90	528	526	528	529		157	157	157	158		110	109	110	111		52	51	52	52
100	528	526	528	529		157	157	157	158		110	109	110	110		52	51	52	51
200	527	524	528	529		157	156	157	157		110	109	110	110		51	51	51	51
300	527	524	528	529		156	156	157	157		110	109	109	110		51	51	51	51
400	527	524	528	529		156	156	156	157		109	109	109	110		51	51	51	51
500	527	524	525	529		156	156	156	157		109	109	109	110		51	51	51	51
600	527	524	525	528		156	156	156	157		109	108	109	110		51	51	51	51
700	528	524	525	528		156	156	156	157		109	108	109	110		51	51	51	51
800	528	524	525	528		156	156	156	157		109	108	109	110		51	51	51	51
900	528	524	525	528		156	156	157	157		109	108	109	110		51	50	51	51

APPENDIX 5: TEMPERATURE MEASUREMENTS

	resistance (kΩ)		10		51		100		510
device	Temperature (°C)								
			nA		nA		nA		nA
17	-20		615038		118194		59634		11356
	-10		593166		113899		57479		10969
	0		572209		109949		55511		10620
	10		552000		106264		53670		10296
	20		533552		102874		51988		9987
	30		516297		99743		50415		9687
	40		500795		96684		48872		9392
	50		485986		93767		47370		9062
	60		471430		90804		45786		8674
18	-20		608973		117066		58932		11232
	-10		588296		112982		56877		10840
	0		568533		109185		55027		10512
	10		549086		105574		53274		10206
	20		531055		102275		51628		9914
	30		514291		99180		50065		9624
	40		499009		96234		48602		9348
	50		484287		93373		47137		9031
	60		470004		90475		45579		8647

19	-20		615670		118021		59455		11331
	-10		594193		113776		57389		10957
	0		573045		109837		55459		10612
	10		552699		106185		53673		10291
	20		534234		102863		52023		9991
	30		517760		99784		50454		9697
	40		502164		96809		48985		9408
	50		487480		93995		47507		9094
	60		473344		91102		45931		8714
20	-20		613468		117925		59450		11319
	-10		592527		113876		57351		10945
	0		572090		110005		55442		10595
	10		552879		106363		53646		10280
	20		534533		103016		51985		9985
	30		517724		99855		50431		9696
	40		502391		96933		48913		9405
	50		487622		94031		47471		9088
	60		473295		91063		45890		8700