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How Fractional are Super-capacitors? Electrochemical Impedance Spectroscopy (EIS) Measurements

by

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Abstract

Super-capacitors are seeing more frequent use in modern electronic designs. Measuring the impedance of such an energy storage device is a good way to characterise how it will behave in real world situations. Therefore this study aims to investigate the present methods of measuring impedance of super-capacitors, with a focus on characterising their properties.

There also seems to be an increasing need for better and more cost effective equipment to measure these devices. Many options exist, and some are well suited to the task however most instruments are either too complicated and difficult to use or too expensive (in the 10's of thousands of dollars) or a combination of both.

This work presents a design for such an instrument which can perform these measurements at a fraction of the cost. The functionality and performance are described and compared to current commercial options. Super-capacitors of varying storage sizes and brands are measured and characterised, and discussed in comparison to batteries.

Acknowledgements

I would like to thank my supervisor, Professor Jonathan Scott for his guidance throughout the project and Sinduja Sehshadri for all her help during the Solartron 1260A investigation, and for all of the useful Python scripts. I would also like to thank Vance Farrow for the use of his robust programmable source meter software and code explanations.

Statement of Originality

I, Gordan Wildschut, declare that this thesis titled, 'How Fractional are Supercapacitors? Electrochemical Impedance Spectroscopy (EIS) Measurements' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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Chapter 1

Introduction

Energy storage devices are used extensively in everything from watches, cell-phones, cars and data centers. This has lead to an increasing need for better and more cost effective equipment to monitor and measure these devices.

Table 1.1: Performance comparison of Super-capacitor and Lithium-ion Battery [1].

Function	Supercapacitor	Lithium-ion (general)
Charge time	1 to 10 seconds	10 to 60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6V nominal
Specific energy (Wh/kg)	5 (typical)	120 to 240
Specific power (W/kg)	Up to 10,000	1,000 to 3,000
Cost per kWh	$10,000 (typical)	$250–$1,000 (large system)
Service life (industrial)	10 to 15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)
Self-discharge (30 days)	High (5 to 40%)	5% or less
Cost per kWh	$100 to $500	$1,000 and higher

Batteries and their various chemistries make up the bulk of devices generally used to store large amounts of energy however there have been other newer devices which have started to make an appearance as well. Advances in capacitor technology over recent years has given rise to a new subset of devices aptly named super or ultra capacitors. As such, the energy density and reliability of super-capacitors are rapidly approaching that of batteries, and in the foreseeable future might rival or even eclipse batteries entirely (see Table 1.1).

1.1 Motivation

Measuring the impedance of an energy storage device is a good way to characterise how it will behave in real world situations. Therefore the aim of this study is to investigate current methods of measuring impedance of commonly used energy storage devices like batteries and capacitors, with a focus on characterising their fractional properties (see Chapter 2). The focus is however, primarily on super-capacitors and how their fractional nature affects usage.

Existing means of performing impedance measurements include precision programmable source meters such as the the Kiethley 2460 with external software, or dedicated instruments such as the Solartron 1260A impedance analyser. Impedance analysers are specifically designed to make impedance measurements, however, most of the available analysers are not suitable for “wet” devices such as batteries and super-capacitors. The Solartron 1260A is the go-to when making these kinds of measurements.

Instruments like these are often expensive (about $52k and $12k for the Solartron and Keithley respectively) and also require substantial time investment in writing the external software required for the device to give reliable and repeatable measurements. In the case of the Solartron 1260A, it is both expensive and requires external software to make it give reasonable results. The Solartron 1260A is discussed and used extensively in this study, and to make it give valid and repeatable results a “recipe” of device settings is provided (see Chapter 3).

A need then arises for a cheaper, more cost effective instrument which can provide a means of obtaining reliable measurements with relative ease as well as providing a better user experience. A design and prototype for such an instrument, dubbed in our group as the "Wildschutron" is discussed in detail and its performance is compared relative to the Solartron 1260A.

Battery based systems such as Uninterruptible Power Supply systems (UPS), have cycle periods in the order of days. Therefore it makes sense that one should make impedance measurements at frequencies below 1mHz, namely the range of 10 mHz down to $10\,\mu$ Hz. This is a recent observation [2].

Super-capacitor technology is steadily evolving and improving. Their energy storage capacity is increasing rapidly as a result, therefore it proves worth while to make similar low frequency impedance measurements on super-capacitors and see how they compare to batteries. The motivation for this is that they might one day replace batteries in some applications.

The impedance of a variety of commercially available super-capacitors of different brands in the range of 1F up to 850F were measured. The outcome of these measurements is discussed in this thesis. The frequencies of interest in this study are primarily sub 10 mHz, as it was found that most studies in the literature do not look any lower than this frequency(again, see Chapter 2).

1.2 Thesis Objectives

1. Review the relevant literature on energy storage devices, especially super-capacitors.
2. Look at the current methods of measuring impedance at frequencies lower than 1mHz.
3. Design a cost effective way of more reliably obtaining these measurements.
4. Measure the impedance of super-capacitors at these low frequencies.
5. Analyse and discuss the measurement results and make comparisons to existing devices such as batteries.

1.3 Thesis Outline

- Chapter 1 gives a brief introduction to energy storage devices, namely super-capacitors and describes the motivation of this study. An outline of thesis objectives is also given.

- Chapter 2 discusses all the relevant background in detail, namely fractional calculus and how it relates to the fractional nature of super-capacitors. The EIS (Electrochemical Impedance Spectroscopy) technique and the Discrete Fourier Transform (DFT) are also described. A review of relevant literature is given to build up a narrative. Lastly conclusions are made which support the motivations of this research.

- Chapter 3 investigates the Solartron 1260A impedance analyser which is the most common instrument used to measure impedance at a wide range of frequencies, including the 10μHz to 1mHz range and describes all the settings required to get reliable and repeatable measurements from it.

- Chapter 4 describes the design and performance of the Wildschutron, which is an instrument which can make the same impedance measurements in the the 10μHz to 1mHz range at a fraction of the cost of the Solartron 1260A.

- Chapter 5 presents measurement results from a variety of super-capacitors. Two distinct mathematical models (Namely the CPE and Split-CPE models [3]) are presented. Models are fitted to a subset of the super-capacitors measured and the results are analysed.

- Chapter 6 discusses the physical significance of the results obtained from the previous chapter. Avenues for further research are also are discussed as well as possible future design improvements to the Wildschutron.

Chapter 2

Background

2.1 Theory and nomenclature

2.1.1 Electrochemical impedance spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) is a technique used to measure impedance of a system over a range of frequencies. This is achieved by applying a small excitation signal (usually a sinusoid) to the system and measuring voltage and the resulting current flowing through it. If we apply a sinusoidal voltage to the system, the resulting current will also be a sinusoid, but phase shifted.

This current can then be analysed as a sum of sinusoidal functions (Fourier series).

By using an expression similar to Ohm's Law, one can calculate the impedance in terms of Magnitude of impedance $|Z|$ and phase shift ϕ [4].

The small excitation signal as a function of time is:

$$V(t) = V_0 \cos(\omega t) \tag{2.1}$$

where $V(t)$ is the voltage at time t, V_0 is the voltage amplitude and ω is the angular frequency (in radians/sec) ($\omega = 2\pi f$).

by using Euler's formula:

$$e^{j\phi} = \cos(\phi) + j\sin(\phi) \tag{2.2}$$

we can obtain a more useful expression in terms of complex exponentials:

$$V(t) = V_0 e^{j\omega t} \tag{2.3}$$

The phase shifted current flowing through the system will then be:

$$I(t) = I_0 \cos(\omega t - \phi) \tag{2.4}$$

where $I(t)$ is the current at time t, I_0 is the current amplitude, ω the angular frequency and ϕ is the phase shift in degrees.

Again by use of Euler's formula we obtain an expression for current in complex exponentials:

$$I(t) = I_0 e^{j\omega t - \phi} \tag{2.5}$$

Now by dividing voltage by current, similar to using Ohm's law:

$$R = \frac{V}{I} \tag{2.6}$$

we obtain an expression for the impedance of the system:

$$Z = \frac{V(t)}{I(t)} = \frac{V_0 \cos(\omega t)}{I_0 \cos(\omega t - \phi)} = Z_0 \frac{\cos(\omega t)}{\cos(\omega t - \phi)} \tag{2.7}$$

And in complex exponential form this reduces to:

$$Z = \frac{V_0}{I_0} e^{-j\phi} = Z_0 e^{-j\phi} \tag{2.8}$$

When analysing results from EIS measurements, it is often quite useful to visualise the complex impedance on Bode plots (see Figure 2.1). Bode plots in EIS show the relationship between magnitude and phase as a function of frequency on logarithmic axes. This is the preferred way of viewing and analysing EIS data, and is used to convey the results of this research.

2.1.2 Discrete Fourier transform (DFT) and Windowing

The Fourier transform deconstructs a time domain representation of a signal into a frequency domain representation. The frequency domain shows the amplitudes (or voltages) present in a signal and at what frequencies. It is another way of looking at the same signal. Often in measurement systems, a signal waveform is sampled and

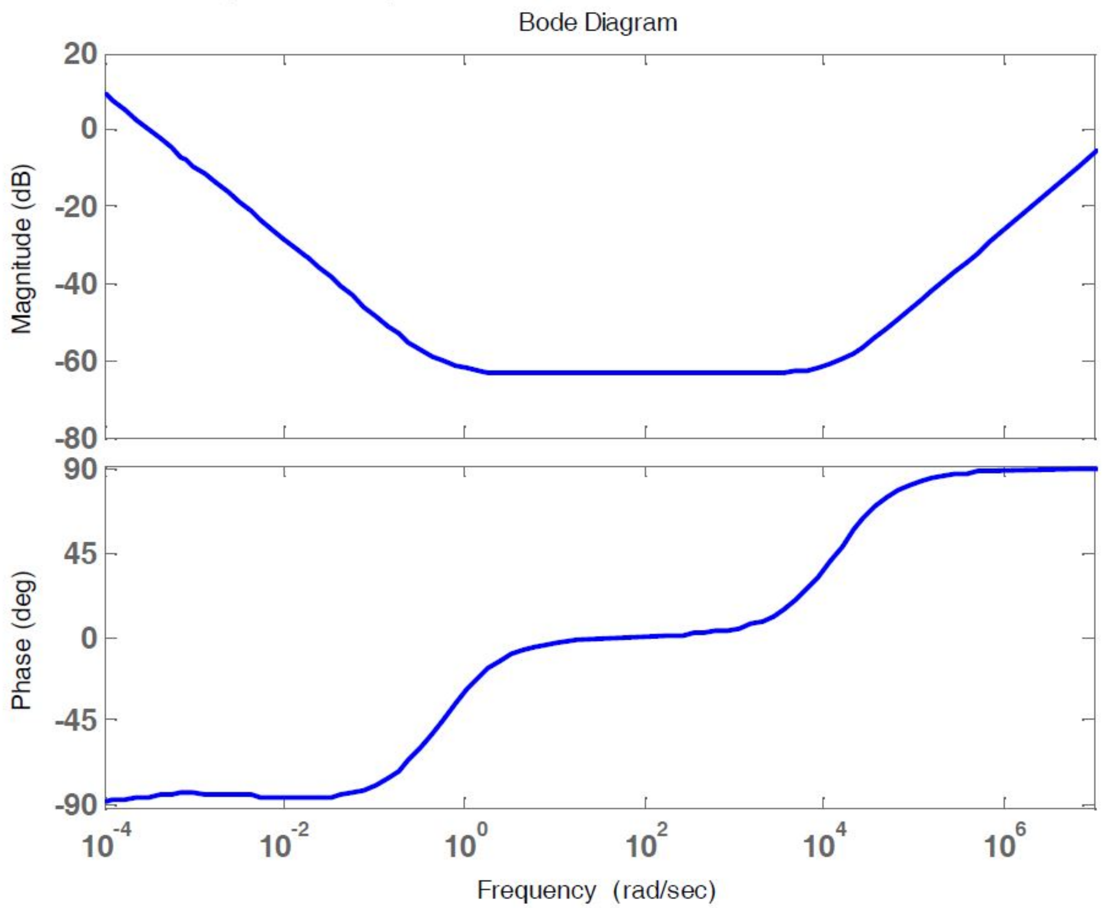

Figure 2.1: Example of a Bode plot (from Shi et al.[5]).

the samples are stored as discrete values. Due to this data not behaving like smooth continuous function, the standard Fourier transform does not work. We can instead use the discrete Fourier transform or DFT. The discrete Fourier transform gives its result as frequency domain components in discrete values or bins [6].

To window a set of sampled waveform data means to multiply the data by a suitable envelope, hence the name "Windowing". This envelope takes the form of a mathematical function, usually a raised-cosine or other "bell" shaped function. What this does is essentially squash the ends of the data set, which removes any possible discontinuity produced by circular replication of the data (the DFT assumes that two endpoints of the time domain waveform are connected together) [7].

2.1.3 Fractional calculus

The theory on fractional calculus summarised here is found in the work of Scott and Hasan [3]. Fractional calculus is the branch of mathematics studying integration and differentiation to non-integer order. Fractional calculus was first defined by Liouville, Riemann and Grunwald in 1834, 1847 and 1867.

The Riemann-Liouville fractional-order derivative is defined as:

$$\frac{\mathrm{d}^\alpha}{\mathrm{d}t^\alpha}v(t) = \frac{1}{\Gamma(1-\alpha)}\frac{\mathrm{d}}{\mathrm{d}t}\int_0^t (t-\tau)^{-\alpha}v(\tau)d\tau \tag{2.9}$$

Where Γ is the Gamma function, and $0 < \alpha < 1$ is an arbitrary real value known as the fractional order [8].

Now, by applying the Laplace transform to (2.9) with zero initial conditions, we get a fractional function which gives us the current-voltage relationship of a fractional capacitor:

$$I(s) = Cs^\alpha V(s) \tag{2.10}$$

And by by re-arranging this equation, we get a function for the impedance of the constant phase element (CPE) in the Laplace domain:

$$Z(s) = \frac{V(s)}{I(s)} = \frac{1}{C_F s^\alpha} \tag{2.11}$$

Here, C_F is the "capacitance" of the fractional capacitor and $0 < \alpha < 1$. A CPE looks like capacitor, but the slope of the magnitude of impedance in a Bode plot will not be -1, but will instead be -α. At very low frequencies, this capacitor-like characteristic appears. This allows us to get an estimate of α by finding the slope of this characteristic impedance magnitude line on the Bode plot. If α is less than 1, we say the capacitor is "fractional".

It was shown by Scott and Hasan [9],[3], that Lithium-ion batteries are fractional. It then begs the question if other "wet" devices like super-capacitors might also be fractional.

2.2 Literature

Modern Super-capacitors, also known as Electrochemical Double Layer Capacitors (EDLC), are relatively new devices in the energy storage device market. Freeborn et al. effectively summarises their widespread usage in the renewable energy, electric vehicle and medical industries [10]. Because they have become so common in various modern-day industries, there is a need to effectively and accurately model their behaviour. This review focuses primarily on literature pertaining to fractional modelling on Super-capacitors and how this kind of modelling has become a more suitable replacement for traditional RC (Resistor-Capacitor) models. This review does not however, cover classical RC models of super-capacitors in any depth, as they are not in the scope of this research.

Historically these types of capacitors have been modelled by increasingly complex RC networks which requires extraction of many circuit parameters from experimental data, and many different approaches are dotted about the literature, see [11],[12],[13],[14],[15] and [16]. Shi et al. describes three different circuit models and how to translate parameters between them so that one may choose the model which best suits their particular device [5].

More recently, fractional impedance models have been employed to more simply and precisely model super-capacitors with fewer parameters[17]. Martin et al. provides a summarised overview of two distinct methods of mathematical modelling of these devices. These are models which have equations based on fractional poles and zeros which can be deduced by graphical methods and fractional "structural modelling" (lumped element modelling) in which the model consists of an RC array containing one or more frequency dependent circuit elements. These fractional models are the Warburg, Bounded Warburg and Havriliak-Negami with 1, 2 and 4 parameters respectively. Lastly they propose a model based on Havriliak-Negami with 9 parameters which fits across all frequencies. They verify this experimentally on two super-capacitors, 5F and 50F, which provides evidence that fractional models fit better than their classical RC counterparts[18].

In 2010, Bertrand et al. demonstrated that the way in which super-capacitors are used must also be taken into account when attempting to effectively model their behaviour. They investigated their usage in Hybrid Electric Vehicles (HEV's), where the devices are subjected to high pulsed currents followed by periods of rest (or relaxation). They accurately model this dynamic behaviour by proposing a new fractional model which encompasses modelling based on voltage dependency and models based on super-capacitor relaxation. They investigate the non-linear behaviour in both the time and frequency domains, and use linear approximation techniques to effectively model the dynamic behaviour around a set of operating points. The model is verified by experiments on a 2600F super-capacitor and on a real HEV current profile. They make special note that during charging and discharging, the model fits well, but is limited by their approximation of the charge-recovery behaviour of the super-capacitor (where the voltage drifts over time) [19].

Mahon et al., investigated four different measurement methods on two different super-capacitors, one commercial and one made in-house. The techniques investigated were Impedance Spectroscopy, Constant Current Charging, Cyclic Voltammetry and Constant Power Cycling. They used each method to extract RC parameters for each device. Early on, the Cyclic Voltammetry method was deemed unsuitable for these measurements due to the commercial super-capacitor having strict voltage requirements and the Cyclic Voltammetry technique being heavily dependent on voltage. They found that the Impedance Spectroscopy and Constant Current Charging methods provided excellent results for super-capacitors under equilibrium conditions (low power), but did not yield similar parameters when the devices were subjected to the Constant Power Cycling techniques (higher power usage). It was found that using a simple RC model greatly underestimated the apparent equivalent series resistance (ESR) when the device was used at constant power. Later on during the investigation, it was found that when they substituted a CPE (constant phase element) for the capacitor in their model, the model fit the experimental data obtained from Impedance Spectroscopy and Constant Current measurements much more closely. It should be noted that they only fitted the R-CPE model to impedance data obtained in the 10 mHz to 1000 Hz range [20].

In one particular study by Wang et al, they looked at very low frequency behaviour and showed that Super-capacitors exhibit transient behaviour over extended periods of time (in the order of months) and can be accurately modelled by a fractional impedance model [2].

Dzielinski et al. uses fractional order models based on time domain step responses. They derive a time domain step response model of a super-capacitor and verify it against results obtained via measurements in the frequency domain. They make special mention that in order to obtain reasonable results from measurements in the time domain, measurements must be made over short periods of time. This is because estimating alpha at high frequencies on super-capacitors is almost impossible (voltage tends to zero) [21], [22].

Freeborn et al. use an indirect measurement technique based on numerically solved least squares fitting to estimate the impedance parameters from voltage exited step responses. Low capacity values of 0.33F, 1F and 1.5F and were measured in a time range of 0.2 to 30 seconds and high capacity values of 1500F and 3000F were measured in the time range of 0.2 to 90 seconds. They obtain alpha values of $\alpha \approx 0.53$ and $\alpha \approx 0.98$ for the small and large sized capacitors respectively. Using these extracted model parameters, they achieve a relative error of less than 3% between simulated and measured responses [10]. The results from this study seems to suggest that α decreases for smaller sized super-capacitors and α approaches 1, for the larger super-capacitors. However this study does not show if this trend still holds if the measurement time period is much longer.

The trends in the literature suggest when modelling super-capacitor behaviour, fractional impedance models fit better with experimental data over a wider range of frequencies than integer order RC models. Fractional models also require less parameters and are less complex. Time-domain methods are quite often used to extract these parameters indirectly. This approach however only provides an estimate of these parameters. Extracting parameters directly via methods like impedance spectroscopy can often provide more accurate results, however models need to be changed to incorporate a constant phase element (CPE) in place of the capacitor to effectively model the low frequency behaviour. It has been demonstrated that this approach provides excellent results, however it was found that none of the literature investigates ultra-low frequency behaviour of Super-capacitors below 10 mHz and into the uHz range [20], [17]. This presents an opportunity for an in depth analysis at these frequency ranges.

Chapter 3

Solartron 1260A Investigation

3.1 Need for an investigation

In past work carried out at the University of Waikato there have been many attempts to get reliable and repeatable measurements out of the Solartron 1260A impedance analyzer on 'non-standard' components. 'Non-standard' meaning the likes of implantable electrodes, super/ultra-capacitors and batteries. Attempts have been made by Hasan [9] and MacCallum [23]. Due to the 1260A's manual being inadequate the problem is most likely the use of less-than-ideal device settings when measuring these components, which we will discuss in this chapter.

3.2 Erroneous measurements

The Solartron 1260A has two primary measurement modes, namely Constant Voltage (CV) mode and Constant Current (CC) mode. A description of these operational modes is given in Appendix C.

Initially, some super-capacitors were measured in the 1F to 100F range with the 1260A in CV mode, as this was the mode used primarily by Hasan [9] and MacCallum [23]. Each component was measured at a single frequency, but repeated ∼10 times. The idea is that the resulting measurement should produce the same value every time. In order to more quickly diagnose what was actually happening in CV mode, one particular setting or DUT condition was adjusted between each batch of measurements. These settings or DUT conditions were namely: DC Bias (DUT), V.AMP, V. BIAS and Frequency.

With this approach and many tests, it was found that as the test frequency got lower (10mHz and below), we started to get erroneous measurements, see Table 3.1. By verifying with a DMM at the end of each run, the final DC Bias on the DUT no longer matched the V. BIAS setting sent to the 1260A. This would indicate that a DC voltage drift occurred.

Table 3.1: Measurements drifting as the frequency is lowered in CV mode.

100F S.Cap (2.7V)	$\|Z\|$ (Ω)	θ (°)
Settings:	0.011811	-13.263
DC BIAS = 1V	0.012342	-15.51
V.AMP = 1V	0.012833	-16.603
V.BIAS = 1V	0.13336	-14.62
FREQ = 1Hz	0.013388	-14.332
	0.013445	-14.549
	0.013256	-14.44
	0.013337	-14.495
	0.013437	-14.468
	0.013347	-14.206

100F S.Cap (2.7V)	$\|Z\|$ (Ω)	θ (°)
Settings:	527.8	-177.59
DC BIAS = 1V	275.01	-185.28
V.AMP = 1V	247.36	-185.81
V.BIAS = 1V	182.9	-190.81
FREQ = 1mHz	172.12	-198.25
	157.04	197.37
	143.61	-209.88
	144.55	-205.35
	128.87	-206.69
	93.9	-219.69

It was suspected that measurements at the lower frequencies ($\leq$ 10mHz) on larger energy storage devices such as batteries or super-capacitors would cause the DC voltage level of the DUT to drift over time. Once sufficient time has passed there would be a substantial mismatch in the DC voltage level of the DUT and V. BIAS setting of the 1260A.

The combination of the "voltage waveform drift issue" described by Hasan [9] and the mismatch between DUT voltage and the V. BIAS setting appears to be what causes the 1260A to produce erroneous results. The 1260A apparently cannot handle this waveform drift. We suspect that it most likely has an adverse effect on the Fourier transform calculation done by the 1260A. We only assume this might be the case, we do not know for certain. This also seems to only be the case in CV mode, as CC mode has no V. BIAS dependency.

This issue becomes a lot more evident when measuring ‘larger’ components such as batteries or super-capacitors but not in “smaller” or “standard” sized components like resistors and smaller capacitors. In the case of smaller capacitors, say in the order of 10’s of microfarads, the 1260A is able to charge them up to the specified V.BIAS level, and maintain this level over all frequencies of interest to produce correct results.

3.2.1 Erroneous measurements in CV mode

Either of the two conditions below, or a combination of both have been found to produce erroneous measurements:

- Test frequencies $\leq$ 10mHz
- DC bias level on the DUT $\neq$ V.BIAS setting of the 1260A

3.3 Correct measurements

In this section we discuss how to obtain reasonable results with CC mode. The reason this mode works best on ‘wet’ cells is most likely due to CC mode not having any DC bias (V. BIAS) dependency like that of the CV mode.

There exists an I. BIAS setting which is used to ‘null’ any DC offset but special care is needed when setting this as the behavior is similar to that of V. BIAS, but in CC mode instead. For the measurements that follow, setting I. BIAS equal to 0, seemed to be fine.

3.3.1 Correct measurements in CC mode

Summarised below are settings to obtain reliable measurements in CC mode: *Note: Maximum current output of the 1260A is 60mA and all settings below are in Amperes*

- For a smaller capacitor (≪1F) set:

  I. AMPL ≈ 0.001

  I. BIAS = 0.0

- For a mid-sized super-capacitor (between 1F and 100F) set:

  I. AMPL ≈ 0.005

  I. BIAS = 0.0

- For larger super-capacitors (≫100F) and batteries set:

  I. AMPL ≈ 0.05

  I. BIAS = 0.0

3.4 Caveats

- Measurements must be made in the 4-terminal measurement (Kelvin contact) arrangement. Usage of coaxial cable is recommended for higher frequencies.

- It was found that readings become noisy past about 10mHz at an integration time of 1 Cycle. It is recommended to increase the number of cycles as the stimulus frequency increases. 6 Cycles is recommended.

- The Solartron does not have any voltage safety limits, so it requires that you monitor the voltage via scope' or other means so as to not exceed the maximum rated voltages of the DUT.

3.5 Measurement verification

Figure 3.1 shows a plot of impedance vs frequency for a HyCap 500F super-capacitor made on the 1260A, and on the Agilent 66332a running Farrow's 'bz' program [24]. The sweep made on the 1260A uses the CC mode settings discussed in section 3. We can see that the measurements made on the 1260A now agree very closely with the results from the 'bz' program running on the Agilent 66332a (made independently).

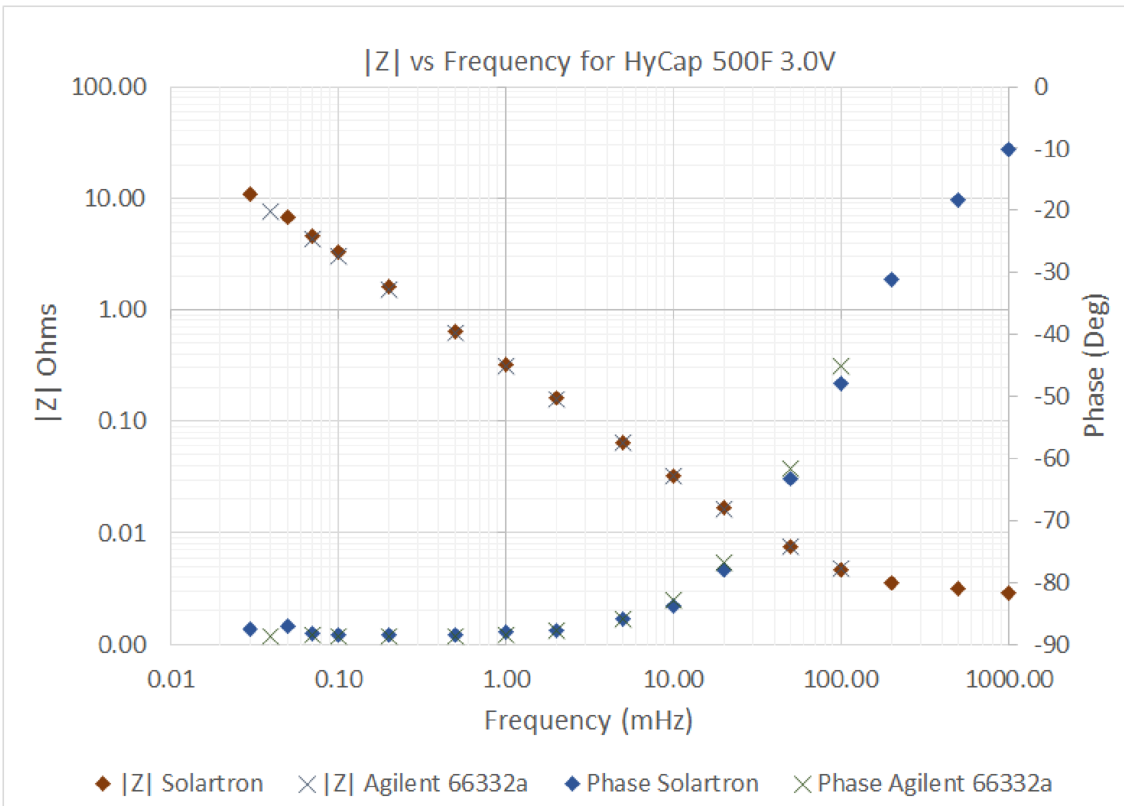

Figure 3.1: Sweep of $|Z|$ vs Freq of a 500F super capacitor made on the Solartron 1260A and the Agilent 66332a using Farrow's 'bz' program.

Chapter 4

Wildschutron Design

4.1 Overview

This chapter provides a summary of the design and performance of the Wildschutron impedance analyzer. A detailed description of the hardware and software is provided as well as verification of device operation and performance. Comparisons are made to impedance data obtained from a programmable source meter, (the Agilent 66332a running Farrow's bz program [24]) and data obtained from the Solartron 1260A impedance analyser.

4.2 Hardware

The hardware is made up of the following blocks (see Figure 4.1):

1. Power supply
2. Processor board
3. Output Current drive
4. Voltage measurement
5. Current measurement
6. Front panel
7. Communication interfaces

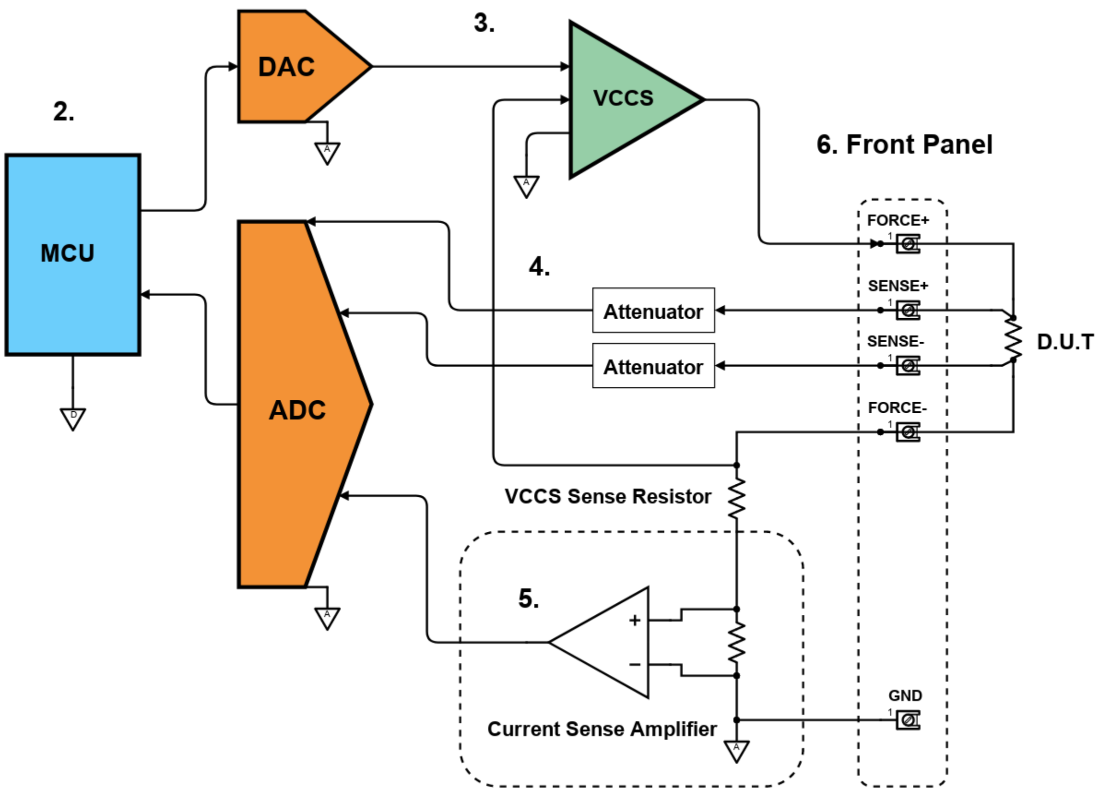

Figure 4.1: Simplified functional block diagram of the analog front end of the Wildscutron, showing the processor (2), output current drive (3), voltage measurement (4) and current measurement sections (5). The associated front panel connections are shown and how they should be connected to the device under test (6). The power supply (1) and communication interfaces (7) sections are omitted for clarity.
Block diagram created using "Scheme-it", the free online schematic and diagramming tool by Digi-Key Electronics Ltd.

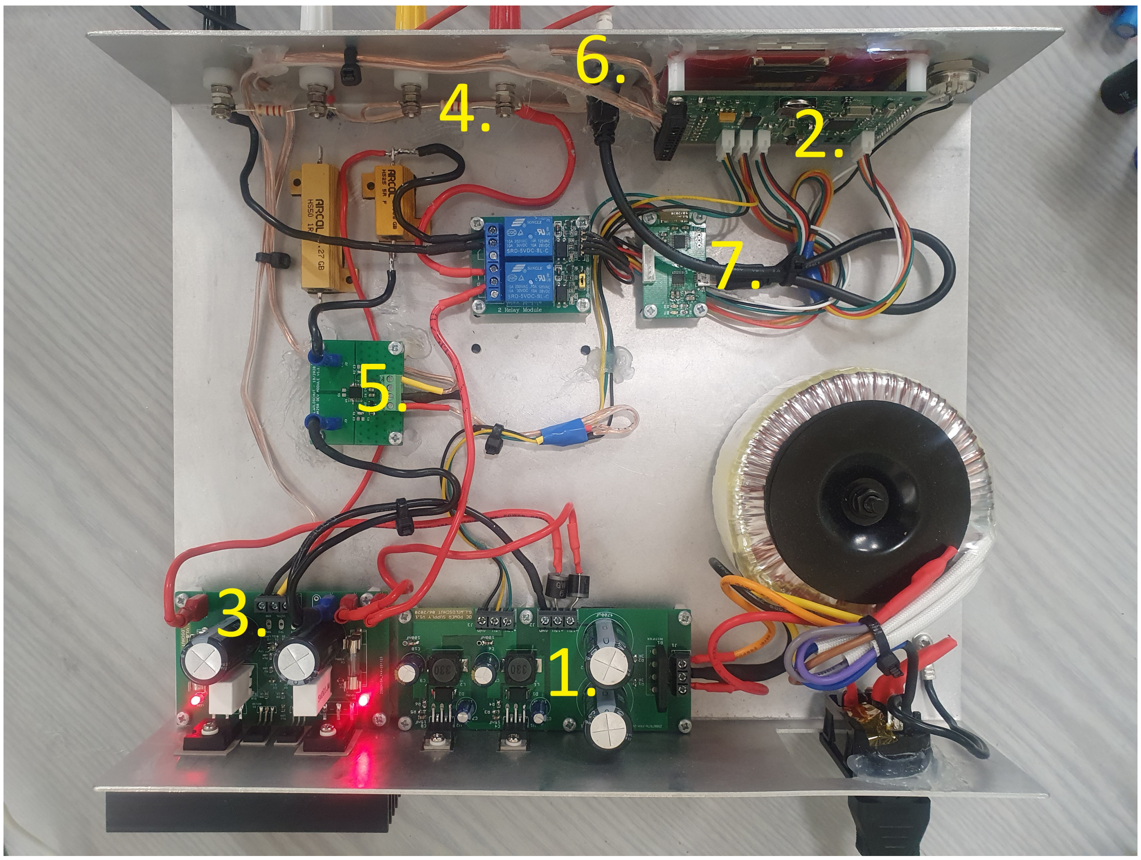

Figure 4.2: The Wildscutron prototype, the power supply (1), processor board (2), output current drive (3), voltage measurement (4), current measurement sections (5), front panel (6) and communication interfaces (7).

4.2.1 Power supply

The power supply for the device consists of:

- a toroidal mains transformer with a power rating of 160VA, two 12VAC secondary windings with a total output current of 6.67A.
- bridge rectifier stage with output smoothing capacitors and bleed resistors, to rectify each secondary output to provide a split rail power supply with +17VDC and -17VDC respectively. These two rails are used to power the voltage controlled current source (VCCS).
- two separate switching regulators powered from the +17V supply which step down the voltage to +12V and +5V respectively. These two supply rails power the Processor board.

4.2.2 Processor board

The processor board features the following:

- 3.3V low noise linear regulator to power the processor.
- The main processor which is the STM32F446, which is an ARM Cortex-M4 based processor clocked at 180MHz. It features plenty of IO and peripheral interfaces with the added advantage of a hardware FPU (floating point unit).
- Coincell battery backup for the which is required by some processor features.
- Various IO interfaces: TFT Display and SD Card connector, Relay control outputs, Serial wire debug (SWD) programming connector, UART connectors and front panel connectors (see Appendix A).
- DAC8552 16-bit Digital to analog converter (DAC).
- ADS1256 24-bit Analog to digital converter (ADC).

4.2.3 Output current drive

Output current drive capability is achieved via the DAC driving a voltage controlled current source (VCCS). The DAC chosen is the DAC8552 from Texas Instruments, which is a 16-bit dual channel ultra-low gitch voltage output DAC.

The VCCS is comprised of a cascaded op-amp input stage for voltage scaling and amplification. This stage is then followed by a complementary darlington output stage to drive current into the DUT. The output stage is designed to output a maximum of 7A and is heat-sinked to the back panel.

Negative feedback is achieved by a sense resistor in series with an INA250 current sensor. These are connected in the low side of the DUT current path through to ground, see Figure 4.1. There are two of these VCCS sense resistor/INA250 current sensor pairs, one for each current range, and either of these are switched in the feedback path via relays to drive and measure the desired output current. These current ranges are ±1A and ±5A respectively. (See schematic A.6 in Appendix A for more information).

4.2.4 Voltage measurement

The voltage is measured between the SENSE+ and SENSE- terminals on the front panel. These two terminals are each first wired through a voltage attenuator (simple resistive divider) to scale the voltage to an appropriate level to then be read by the onboard 24-bit ADC which is configured to read voltage in differential mode. The ADC used is the ADS1256 by Texas Instruments, which is a very low noise, 24-bit ADC with a 4th-order, delta-sigma modulator and programmable digital filter. It features extremely low noise performance (up to to 23 noise-free bits) and ±0010% nonlinearity with data output rates up to 30kSPS. Data is output via the four wire SPI interface and read by the processor.

4.2.5 Current measurement

The current is measured low side (ground referenced) via the INA250 current sense amplifier which gives an voltage output proportional to load current. This voltage is read by the ADC, and converted into a current value in software. The INA250 was chosen as it integrates the shunt resistor in the same IC package. Because of this, low temperature drift and high accuracy is achieved (Gain error is 0.3% max). INA250 devices are available in four different gains: 200mV/A, 500mV/A, 800mV/A and 2V/A. Two of these devices with different gains are used, these are 500mV/A and 2V/A for the 5A and 1A current measurement ranges respectively.

4.2.6 Front panel

The front panel has a color TFT display which is used to display diagnostic information to the user. There is a single push button with an integrated RGB LED which is used for user input and status indication. Next to the TFT display there is a female micro USB connector for use for the programmable source mode of the device, see section 4.2.7.

The DUT measurement terminal connections are:

- Force + (or Force Hi)
- Sense + (or Sense Hi)
- Sense - (or Sense Lo)
- Force - (or Force Lo)

And are intended to be used in the"Four-terminal" Kelvin sensing connection arrangement when measuring a DUT, as is standard for most commercial programmable source meters and impedance analyzers.

4.2.7 Communication interfaces

The device features two separate UART interfaces, one for debug purposes and one for use when the device is used in the programmable source mode. The debug UART is wired into an RS232 converter which has the standard serial DB9 connector mounted to the back panel. The UART used for programmable source mode is wired into an FT231 USB to serial converter which has a female micro USB connector mounted on the front panel next to the TFT display.

4.3 Software

The Wildschutron device has two operational modes, these are the Programmable Source and Automatic Measurement modes respectively.

In Programmable Source mode, the device behaves as a standard programmable source meter, much like the Kiethley 2460. Time elapsed, Voltage and Curent are displayed on the TFT display and external software is required to drive the device via the front panel USB serial interface.

In Automatic Measurement mode, the device acts as a stand-alone low frequency impedance analyzer with the advantage of requiring minimal user input. This mode makes heavy use of a modified version of Scott's DFT implementation [7](provided with permission) to make multi-tone measurements. The idea, and implementation of equal charge movement from Farrow's 'bz' program is also used to remove the problem of steady voltage drift over time [24] (see Chapter 3). A code excerpt of the DFT and equal charge movement implementation is provided in Appendix B, B.2.

The user need only send a list of measurement sweep settings and press the start button to begin. Cycle number, Time remaining, Voltage and Current are displayed on the TFT display while measurements are in progress (see Figure 4.3). Data is saved to the external SD card and output to the debug UART interface. The SD card interface supports large SD cards (up to 128GB) and the exFAT filesystem.

Figure 4.3: Cycle number, Time remaining, Voltage and Current are displayed on the TFT display while measurements are in progress.

Data is logged in two formats:

- .tvi file format (Time, Voltage, Current).
- .fmp file format (Frequency, Magnitude, Phase).

Both are simple text file formats, with three columns each delimited by spaces. The .tvi format logs Time in seconds, Voltage in Volts, and Current in Amperes respectively. This file is created on the SD card and data is logged to it at each sample period. The .tvi file can get quite large (in the order of GB for low frequency sweeps), so it is only logged to the SD card and not output to the debug UART interface.

At the end of each sweep, an .fmp file with frequency, magnitude of impedance and phase data is generated and saved to the SD card. One line of data per tone is logged to the file. The contents of this file is also output to the debug UART interface.

4.4 Testing and verification of performance

To test basic operation, some low value power resistors were measured at 6 tones with a current bias (IBIAS) of 100mA (see Figure 4.4). The results are tabulated in Table 4.1.

We can see that the measured values match to within the rated tolerance of each resistor (5% resistors). Phase is very close to 0 degrees, as is true for purely resistive elements. This verifies basic operation of the analog front-end and the software to some extent.

Results from some more concrete tests are provided in Figure 4.7 and Figure 4.8. In the first test, impedance measurements from the Wildschutron made on the HyCap 500F super-capacitor (Figure 4.4) are compared to the measurements made on the Solartron in the last chapter (see Chapter 3). From this comparison plot we can see that the values for impedance and phase match very closely at the frequencies measured by the Solartron. The values for impedance as we get closer to 10uHz seem

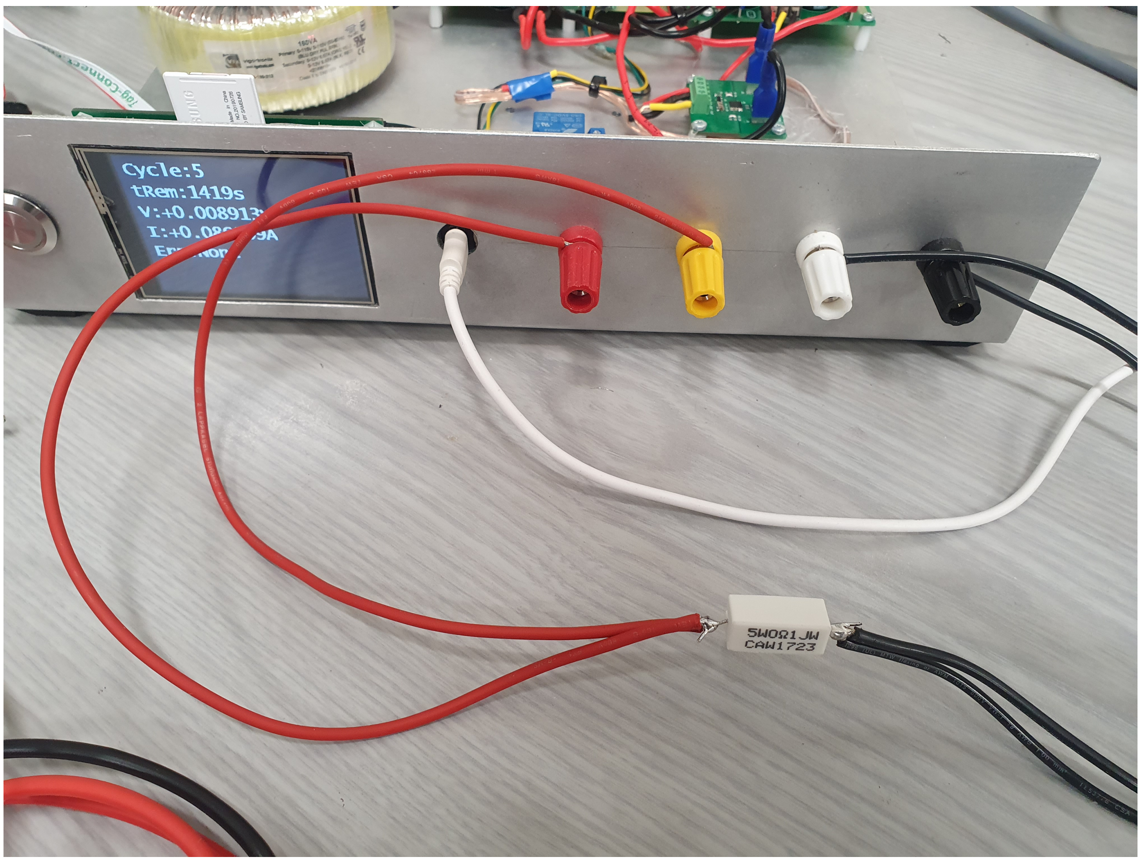

Figure 4.4: 4-wire measurement of a simple low value power resistor.

to begin to deviate ever so slightly, this is most likely an artifact of the DFT algorithm used, so there remains some room for improvement at the ultra-low frequency end.

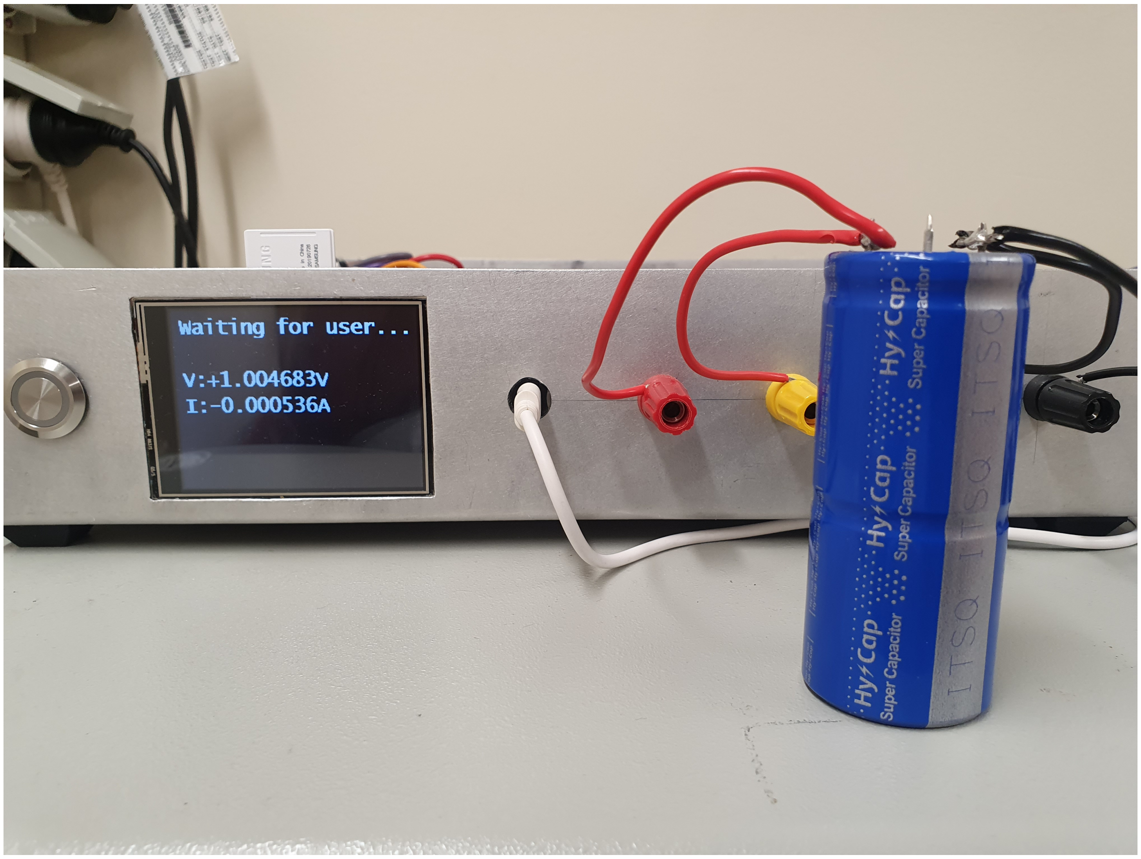

Figure 4.5: 4-wire measurement of the HyCap 500F super-capacitor.

In the second test, impedance measurements are made on a standard 18650 lithium-ion cell (Figure 4.4). Measurements made on the Wildschutron are once again compared to those made on the Solartron. We observe that the measurements do in-fact match very closely, confirming that the Wildschutron performs just as well on batteries.

4.5 Limitations

- In automatic measurement mode, the device is currently limited to a minimum integration time of 6 Cycles. This becomes an issue once measurements are being made in the lower end of the frequency range. Measurement cycle periods

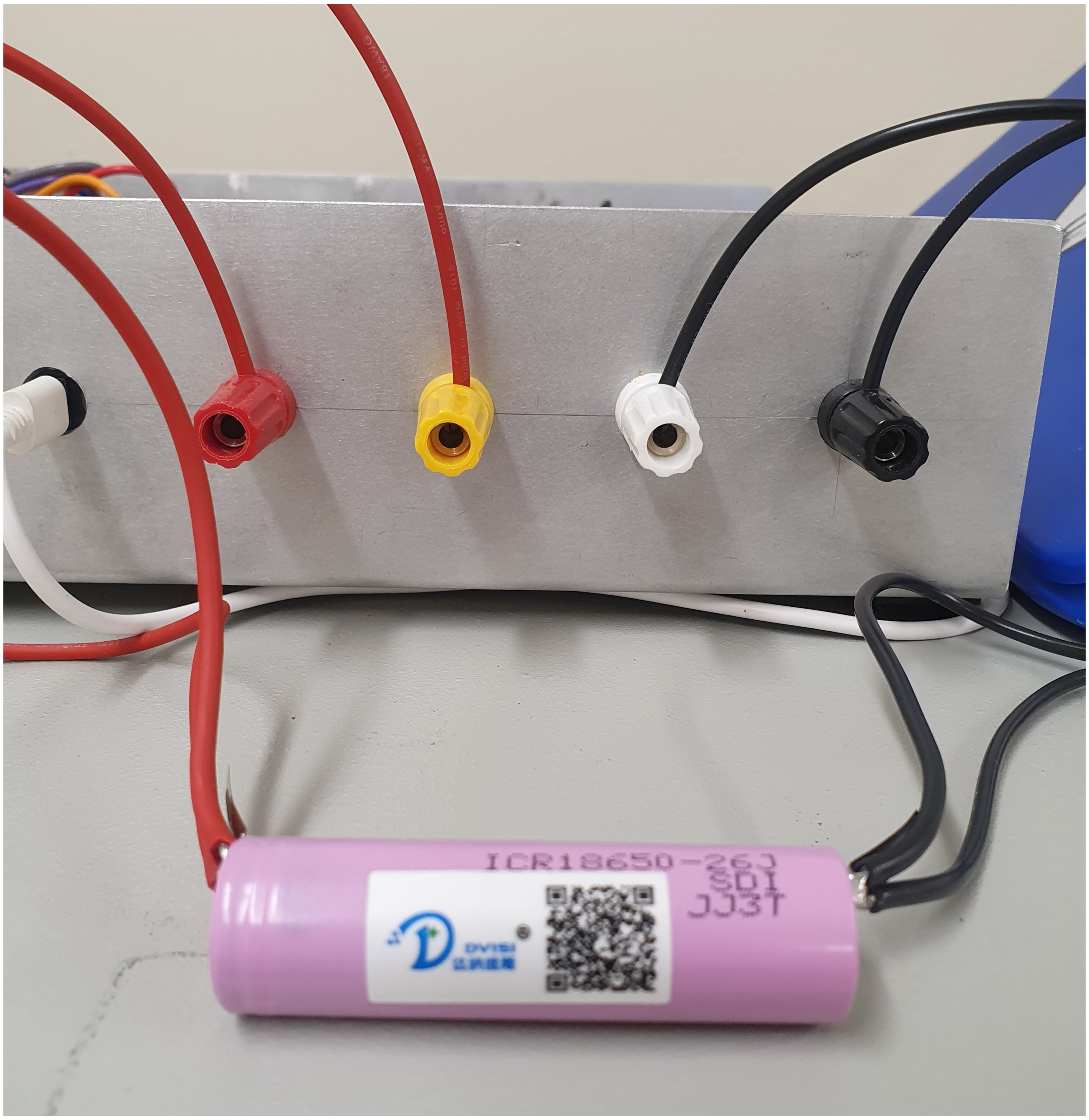

Figure 4.6: 4-wire measurement of the 18650 Li-ion cell.

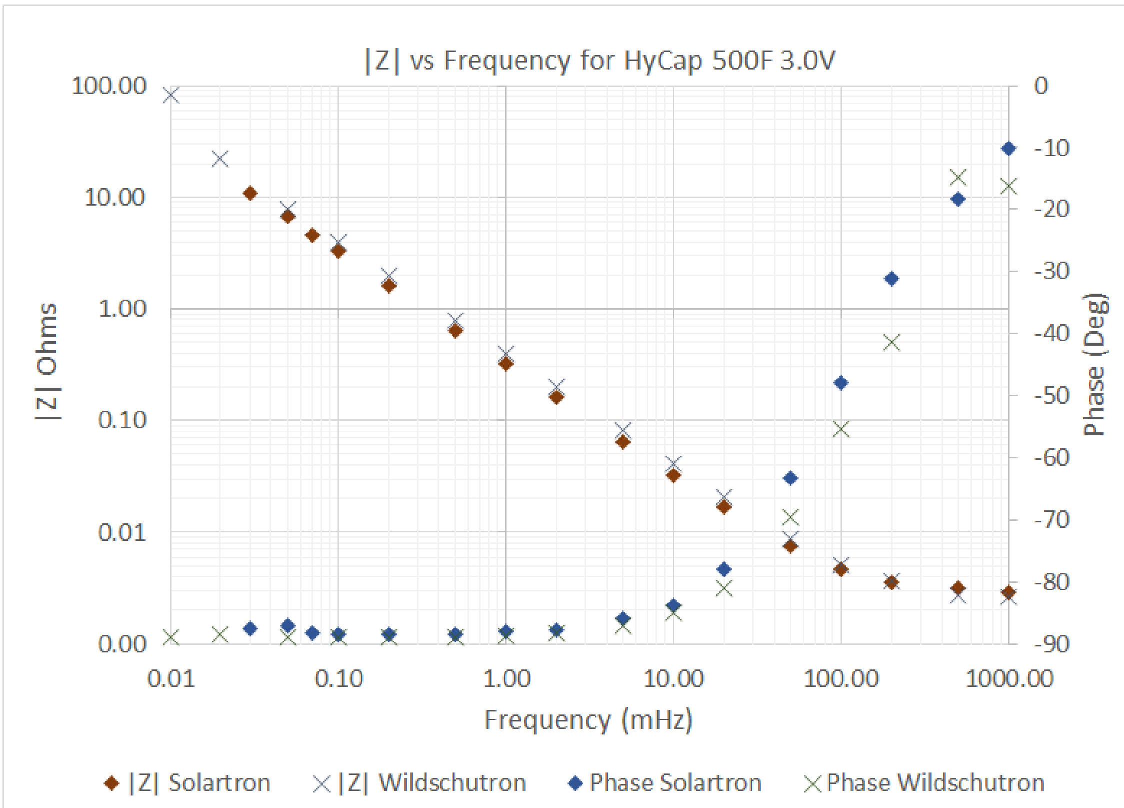

Figure 4.7: Impedance measurements from the Wildschutron made on the HyCap 500F super-capacitor are compared to the measurements made on the Solartron in the last chapter (see Chapter 3). From this comparison plot we can see that the values for impedance and phase match very closely at the frequencies measured by the Solartron. The values for impedance as we get closer to 10uHz seem to begin to deviate ever so slightly, this is most likely an artifact of the DFT algorithm used, so there remains some room for improvement at the ultra-low frequency end.

Table 4.1: Three low value power resistors measured at 6 different tones. We can see that the measured values match to within the rated tolerance of each resistor (5% resistors). Phase is very close to 0 degrees, as is true for purely resistive elements.

1000mΩ		
mHz	$\|Z\|$ mΩ	θ
1.00	1001.86	-359.99
2.00	999.52	-360.00
5.00	998.14	-359.99
10.00	997.88	-0.02
20.00	997.18	-360.00
50.00	997.71	-0.01

100mΩ		
mHz	$\|Z\|$ mΩ	θ
1.00	101.65	-0.02
2.00	100.83	-360.00
5.00	100.29	-0.01
10.00	100.11	-0.01
20.00	100.03	-359.99
50.00	99.94	-359.99

25mΩ		
mHz	$\|Z\|$ mΩ	θ
1.00	24.69	-360.00
2.00	24.79	-0.01
5.00	24.80	-359.93
10.00	24.81	-359.94
20.00	24.83	-360.00
50.00	24.81	-0.01

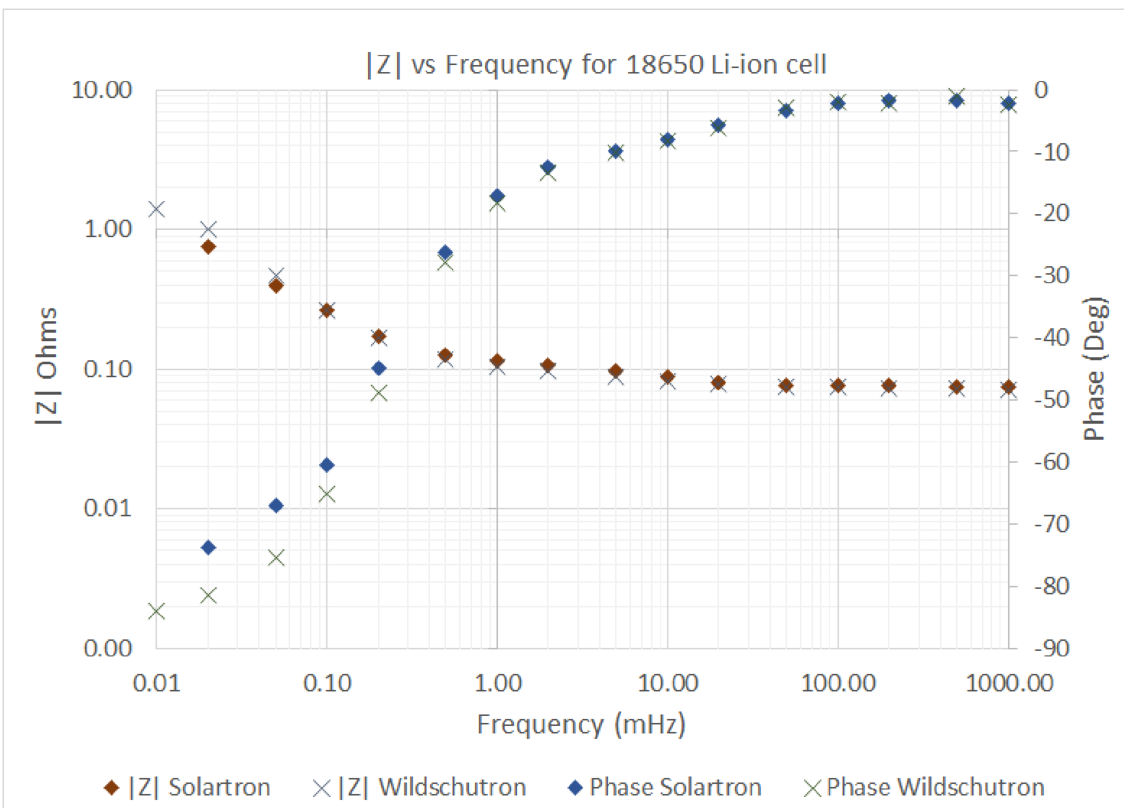

Figure 4.8: Impedance measurements made on a standard 18650 lithium-ion cell. Measurements made on the Wildschutron are once again compared to those made on the Solartron. We observe that the measurements do in-fact match very closely, confirming that the Wildschutron performs just as well on batteries.

become extremely long, in the order of weeks. This is by nature of the DFT implementation used.

This could be remedied by implementing the “Finer Fit” algorithm as described in [25], which is an approach which performs spectral resolution at known frequencies by iterative, optimising fit of multi-sine. If implemented correctly, this could reduce the total number of cycles required to about 1.5 cycles.

- At present, the analog front-end cannot measure negative voltages. This imposes the requirement of having to set a constant DC offset when driving current into non-wet cells.
- Theoretical maximum sample rate is 30kSPS (30kHz), by nature of the ADC chosen. Currently the device does not sample that fast, as other tasks are interleaved whilst sampling (such as TFT screen and SD Card reading/writing).

Chapter 5

Super-capacitor Measurement and Analysis

5.1 Measurement Setup

5.1.1 Device preparation

Firstly, the Super-capacitor to be measured is pre-charged to half of the maximum rated voltage on the bench power supply. The reason for this pre-biasing stage is to make sure that the Solartron 1260A does not drive the voltage negative. It is then left on the power supply for a couple of hours to settle and reach equilibrium. Then it is taken off the bench power supply and the voltage at the terminals of the Super-capacitor is verified with a digital multi meter. Once this voltage has been verified to be more or less close to half the maximum rated voltage, the super-capacitor is connected to the Solartron 1260A as shown in Figure 5.1. This procedure is repeated for each different device measured.

5.1.2 Solartron Python Script

A modified version of the script provided by Hasan [9] was used to control the Solartron 1260A. The two main modifications to the script are the ability to switch the device into Current mode, and the ability to adjust the integration time in number of cycles. The script sets up the device to do a “manual sweep” of frequencies between 10Hz and the 10’s of μHz range. For frequencies below 1mHz, the script makes

Figure 5.1: Device under test connected to the Solartron 1260A in the 4-wire arrangement.

measurements with an integration time of 1 cycle. This is primarily because measurements made at these lower frequencies take a long time - in the order of days for the lowest frequencies. For frequencies 1mHz and above, the script uses an integration time of 6 cycles, as these measurements are faster and prone to noise. As data is receieved from the Solartron 1260A, it is written to the python terminal window and written out to a .fmp text file, one line per tone. A copy of this script is provided in Appendix B, 5.1.2.

5.2 Results

A total of 12 different super-capacitors were measured in the 10Hz to 10μHz range. Various brands were selected to give a good indication if trends are independent of brand in the results. Datasheets for all capacitors is provided in Appendix D.

The smaller sized super-capacitors were only measured down to 30μHz due to limitations of the Solartron 1260A. The DC voltage drift at lower frequencies was found to be more pronounced than on the larger sized super capacitors 20F and above. Therefore as frequency got lower into the μHz range on these smaller devices, the voltage at the super-capacitor terminals needed to be monitored as to not go below zero or exceed the maximum rated voltage of the super-capacitor.

The magnitude of impedance vs frequency and phase vs frequency comparisons for the devices measured can be seen in Figures 5.2 and 5.3 respectively. In the magnitude of impedance vs phase plot, the fractional order parameter α is estimated by taking the slope of the straight portion of the magnitude of impedance from 10mHz down to the lowest frequency for all super-capacitors measured. This value was chosen as all points 10mHz and lower in frequency, lie on this straight line portion of the plot.

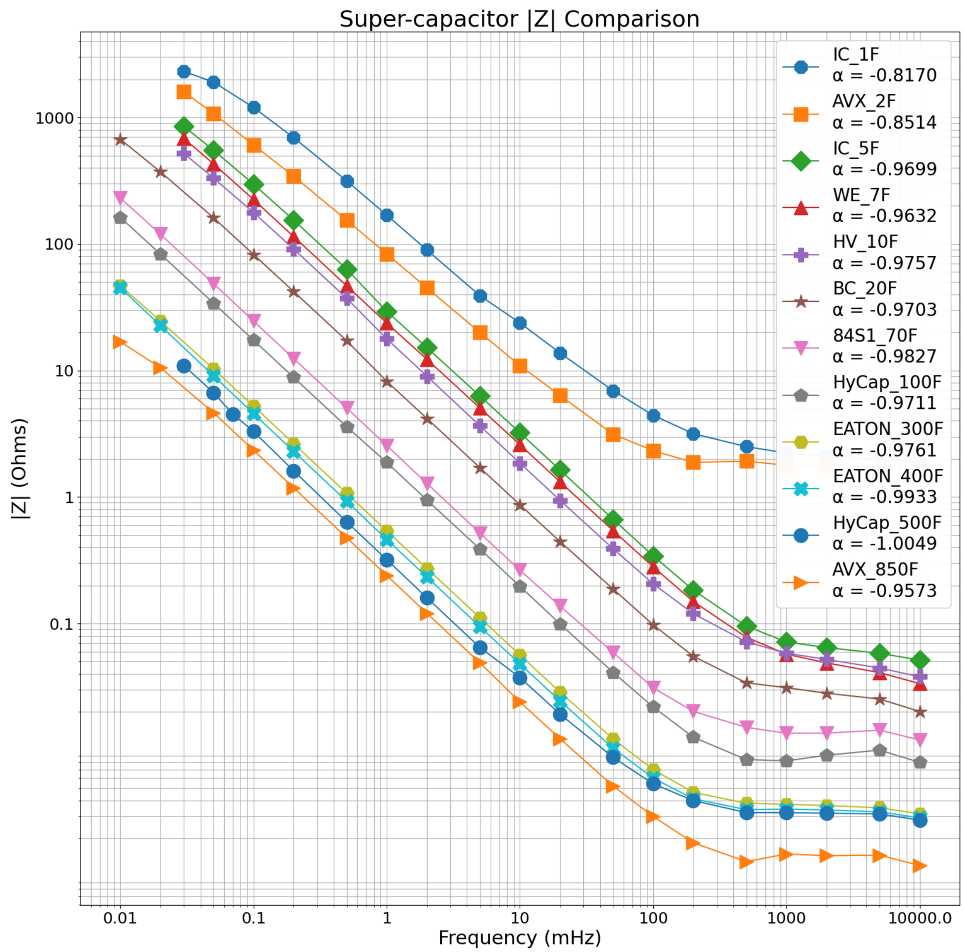

Figure 5.2: Magnitude of impedance comparison for all super-capacitors measured. The fractional order parameter α is estimated by taking the slope of the straight portion of the magnitude of impedance from 10mHz down to the lowest frequency. *Plot made with Seshadri's bode plotting Python script.*

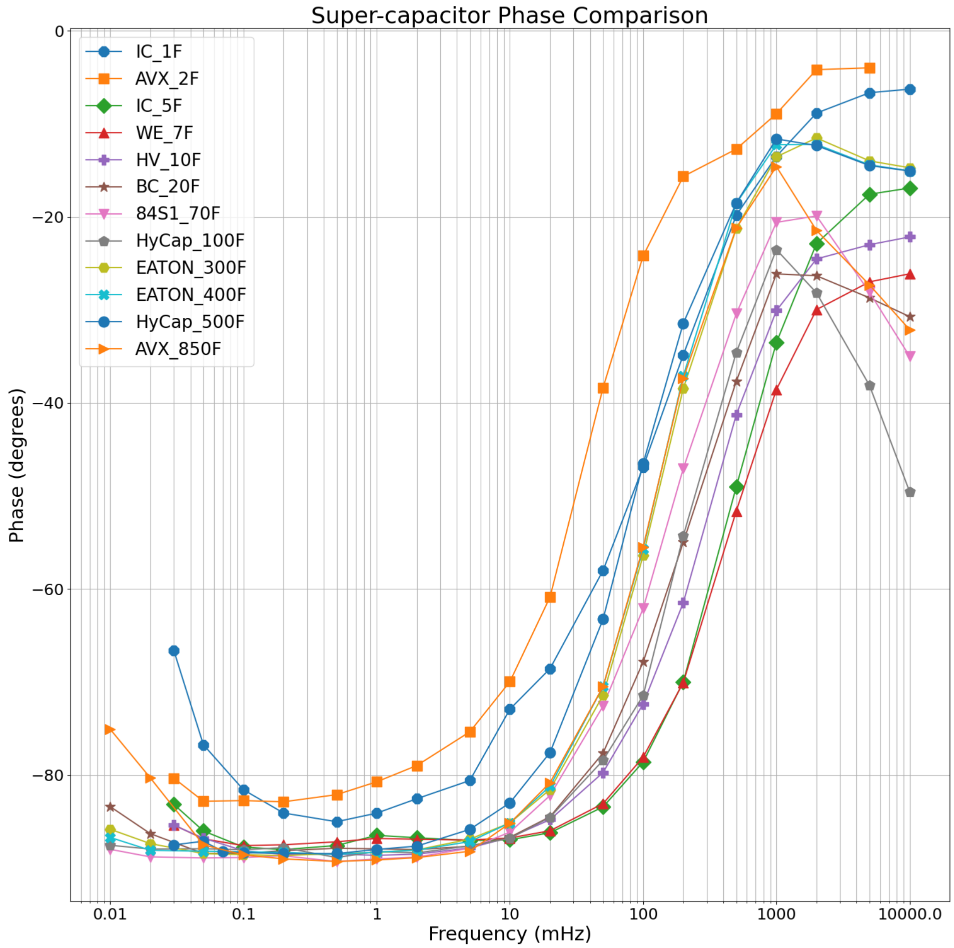

Figure 5.3: Phase comparison for all super-capacitors measured. We can see that the phase generally tends to flatten out at around -88 degrees across larger capacity devices, however some devices, mostly those with lower capacity, exhibit a phase reversal past the 100uHz region of the plot.
Plot made with Seshadri's bode plotting Python script.

5.3 Modelling

From the literature [9], a fractional capacitor can be modelled by a series resistor R_s in series with a CPE.

A Python script to generate the SPICE netlist for the R-CPE model was kindly provided by Seshadri, (see Acknowledgements).

To verify that the R-CPE model [9] fits with experimental data, the model was fitted to one of the super-capacitors measured, see 5.2. The model was fitted to impedance data only, using the extracted parameters α and R_s from experimental data. These model fit is shown in Figure 5.4. Generated SPICE netlist is given in Appendix B, B.3.

From Figure 5.4, we can see that the model fits very closely near the CPE section of the plot, but deviates as we approach the corner and into the series resistance section. This deviation might be fixed by careful adjustment of the R_s model parameter.

This result confirms that super-capacitors can in fact be modelled by the R-CPE model.

5.4 Analysis

In Figure 5.2 we do in-fact observe the general trend that α decreases as the storage capacity gets smaller. This confirms the work of Freeborn et al. [10], however the decrease in α is not as dramatic as their results show. They very well may be over-estimating the decreased α as a result of their time-domain using such short time intervals. Regardless, this is only significant for super capacitors of a couple of Farads, around 2F and smaller.

Figure 5.3 gives a phase comparison for all super-capacitors measured. We can see that the phase generally tends to flatten out at around -88 degrees across larger capacity devices, however some devices, mostly those with lower capacity, exhibit a phase reversal past the 100uHz region of the plot. This is most likely an artefact

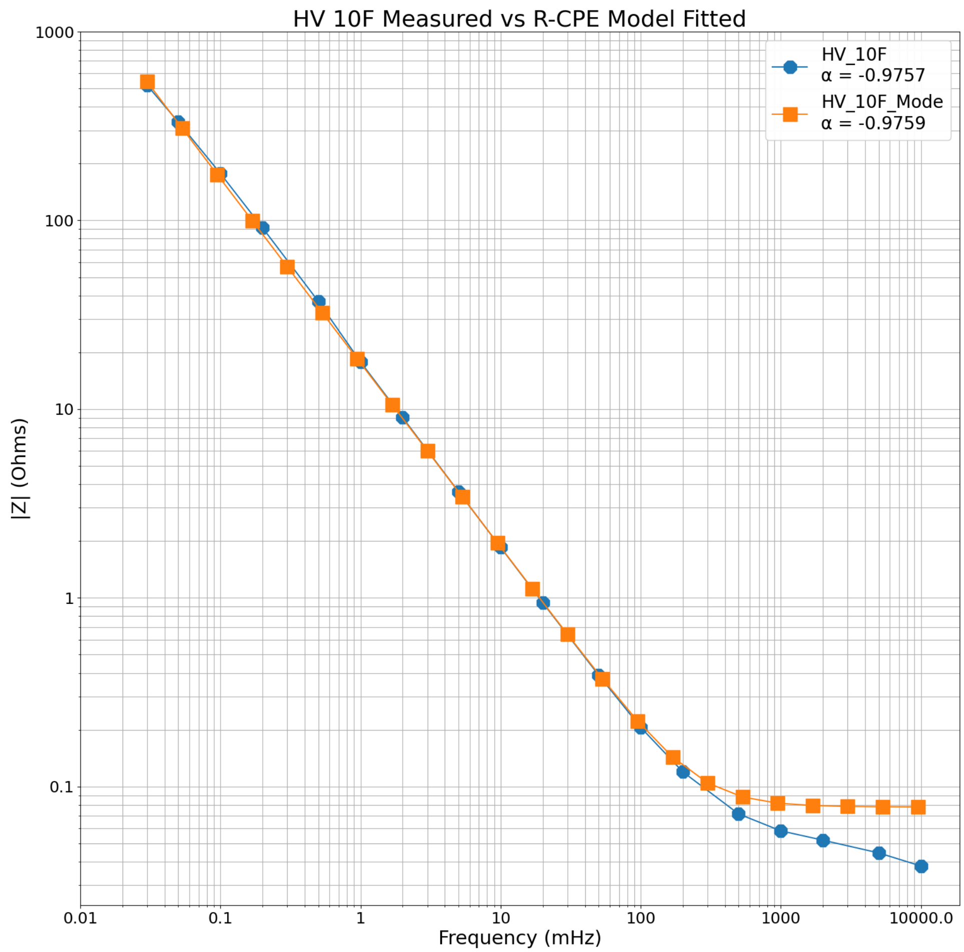

Figure 5.4: Verification that the R-CPE model fits with experimental data from a super-capacitor, using the extracted model parameters α and R_s. We can see that the model fits very closely near the CPE section of the plot, but deviates as we approach the corner and into the series resistance section. This deviation is easily fixed by careful adjustment of the R_s model parameter.
Plot made with Seshadri's bode plotting Python script.

imposed by the Solartron 1260a, as it lacks the equal charge movement feature of the Wildschutron and Farrow's 'bz' program [24]. It is most likely charging the device past the rated voltage of the super-capacitor at the end of the run.

The effects of the fractional order parameter α is physically significant in batteries as this plays an important role in state-of-health [9]. This was found not to be the case for most larger super-capacitors 10F and above, as α is nearly equal to one, meaning that the super-capacitor behaves more like a pure capacitor and less like a fractional capacitor. For smaller sized super-capacitors, their apparent fractionality might prove useful in some niche applications, however it is unlikely to be as significant as fractionality in batteries.

Chapter 6

Conclusions

6.1 Conclusions

- This work is the first to measure below a frequency of 1mHz on Super-capacitors.

- The effects of the fractional order parameter α is quite significant in batteries as this plays an important role in state-of-health. This was found not to be the case for most larger super-capacitors 10F and above, as α is nearly equal to one, meaning that the super-capacitor behaves more like a pure capacitance.

- Super-capacitors are not all equal, some have lower α values as seen in the smaller sized devices measured (below 10F) and seen in the work of Freeborn et al. [10]. The general trend observed was that α tends to decrease as super-capacitor storage capacity decreases.

- There seems to be a dire need for better measurement equipment. Existing solutions are either too expensive (Kiethley 2460), or too complicated and unwieldy to use (Solartron 1260A), or a combination both.

- A design and prototype for a low cost impedance analyzer (The Wildschutron) is provided and shown to perform as well as the Solartron 1260A in the ultra-low frequency ranges.

6.2 Future Work

- There exists so called hybrid lithium-ion super-capacitors. It might prove worthwhile to measure and analyse the fractionality of these sorts of devices and compare to existing super-capacitors and batteries.
- Investigate hybrid R-CPE models like the Split-CPE [3] and see how they fit to super-capacitor data.
- Implement Finer-fit [25] to reduce required number of cycles of Wildschutron down to one and a half (see Chapter 4).
- Address the various limitations discussed in Chapter 4.
- Finalise the Wildschutron design and turn it into a product.

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Appendix A: Wildschutron Schematics

A.1 Processor Board Schematic

A.2 Processor Board Analog Frontend

A.3 Comms Interface

A.4 Power Supply

A.5 Current Sense Amplifier

A.6 Voltage Controlled Current Source

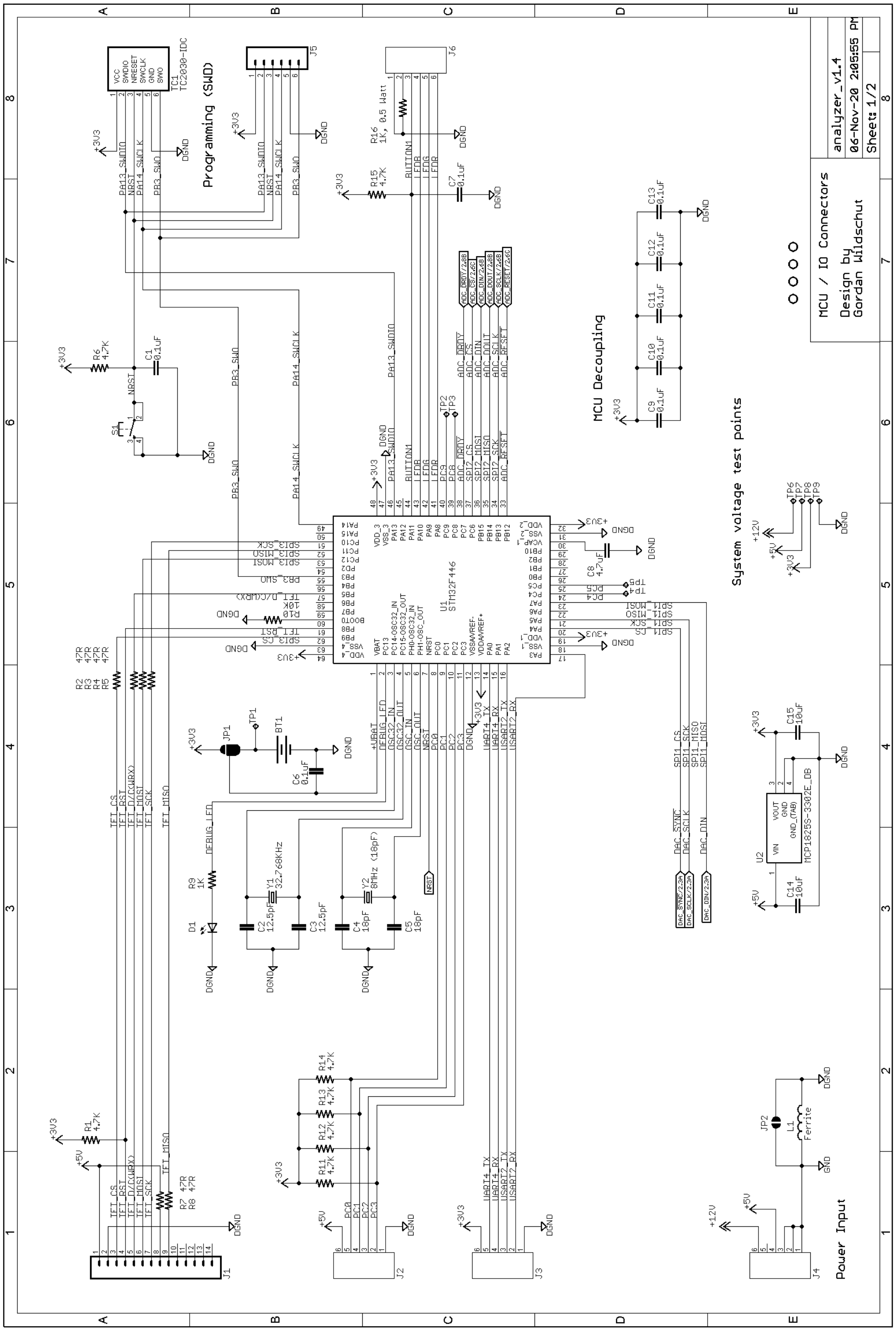


Figure A.1: Schematic: Processor Board

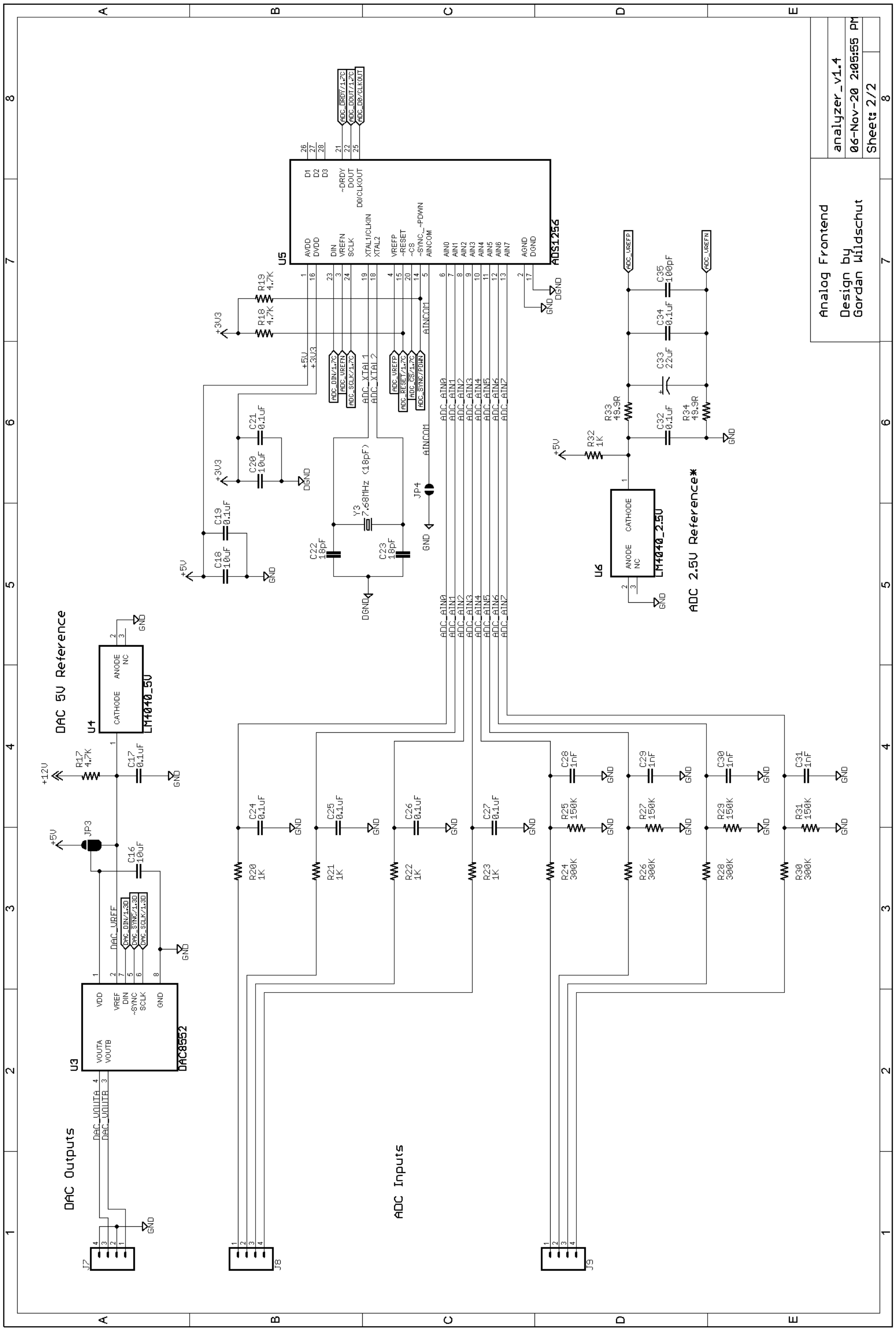


Figure A.2: Schematic: Processor Board Analog Frontend

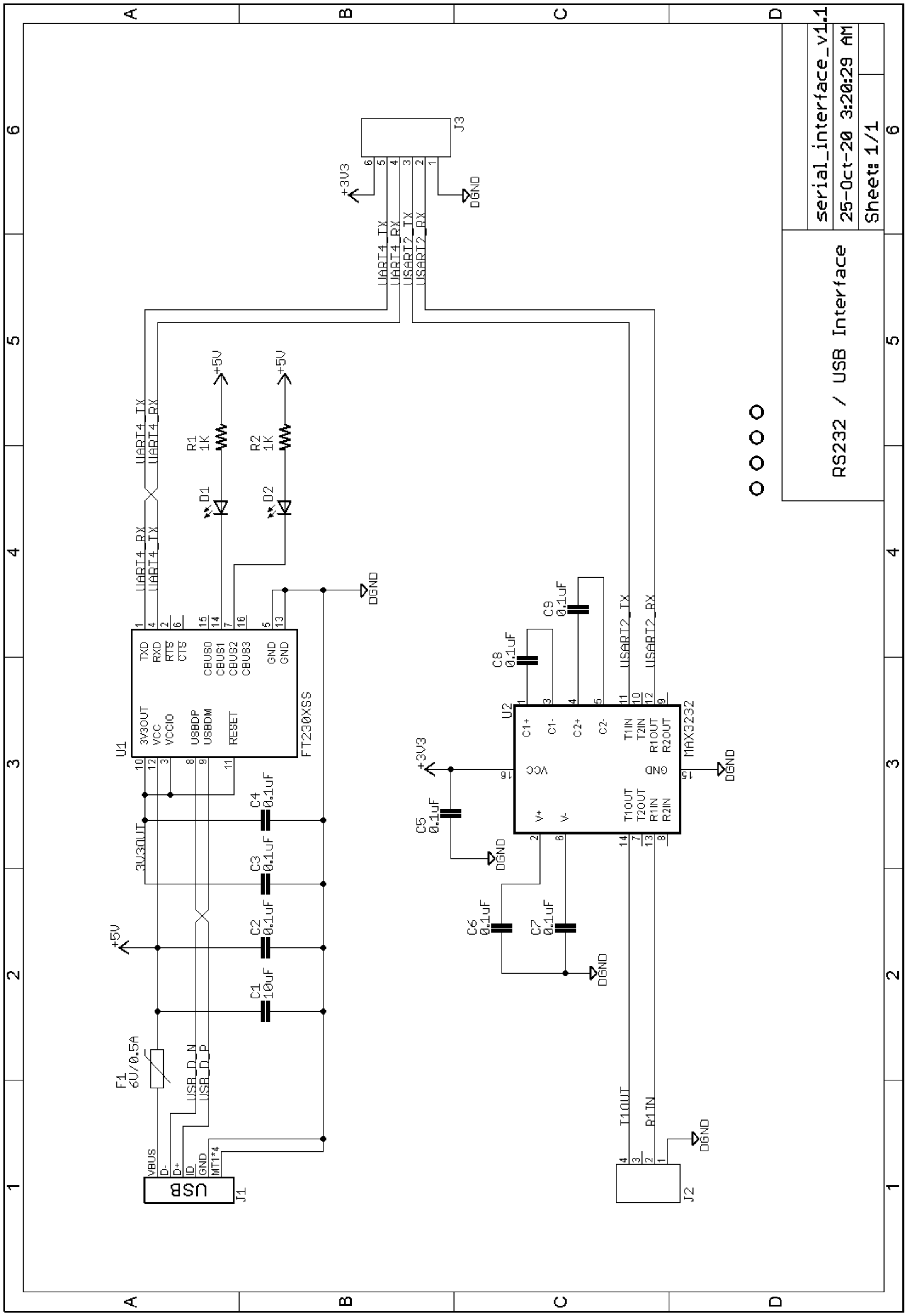


Figure A.3: Schematic: Comms Interface

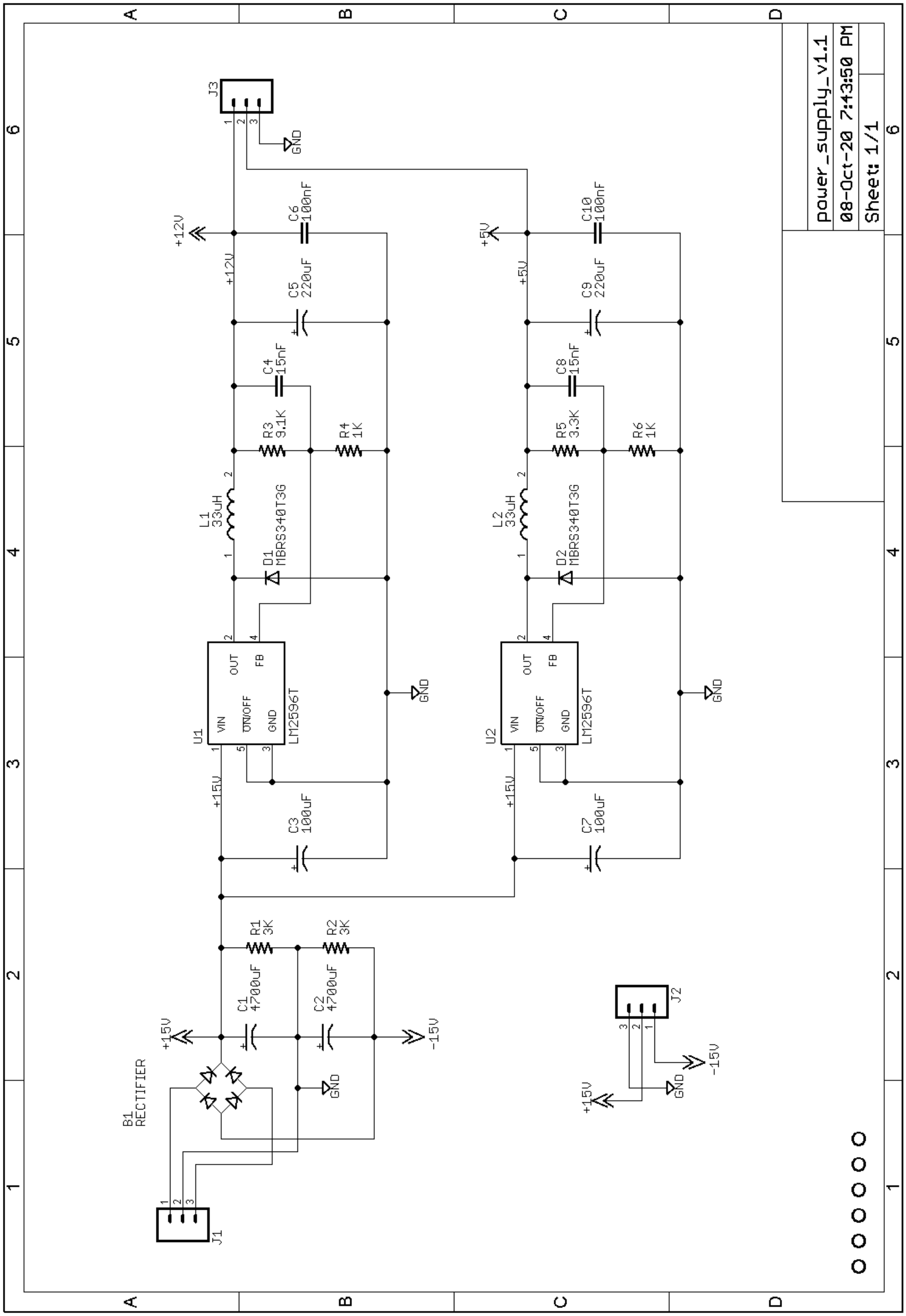


Figure A.4: Schematic: Power Supply

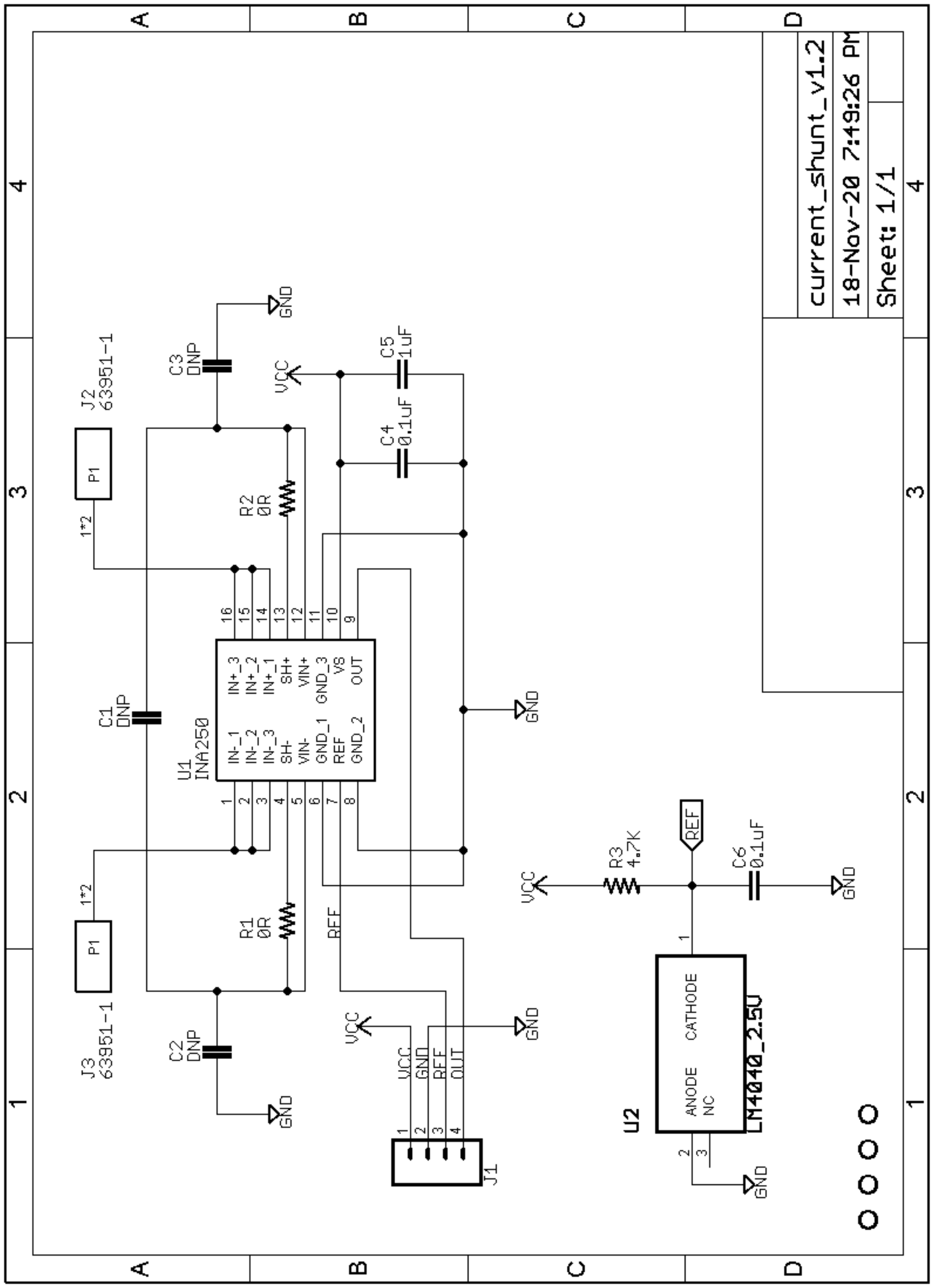


Figure A.5: Schematic: Current Sense Amplifier

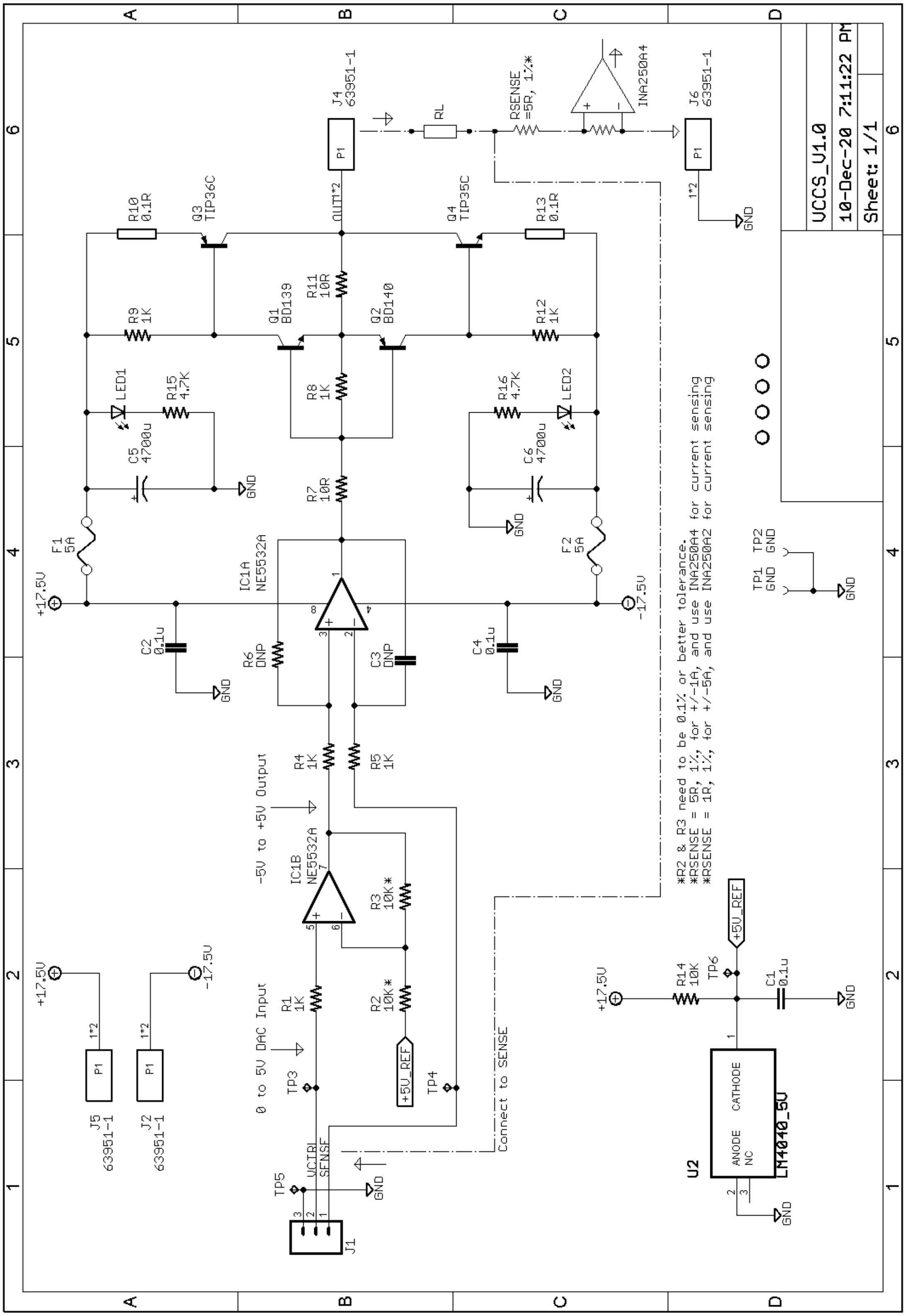


Figure A.6: Schematic: Voltage Controlled Current Source

Appendix B: Code excerpts

B.1 Python Scripts

Listing B.1: Solartron 1260a script

```
import visa
import time
from datetime import datetime
import array
import math
from pyvisa import VisaIOError

print(" --- Solartron 1260 --- ")

# Function for sending messages to solartron with delay included
def send(msg):
  sol.write(msg)
  time.sleep(0.001)
# Min required time between consecutive command sends to Solartron

# Get connected GPIB devices
rm = visa.ResourceManager('C:/Windows/System32/visa32.dll')
resources = rm.list_resources()

# Get Solatron 1260
sol = rm.open_resource('GPIB1::10::INSTR', read_termination='\r\n', write_termination
    ='\r\n', send_end=False)

# Attempt to connect with Solartron by requesting IDN (i.e, "What are you ?")

try:  # If connection is succesful, print the IDN
  IDN = sol.query('*IDN?')
  if IDN != '':
    print("Solartron connected successfully. " + IDN)
except VisaIOError:
  # If connection times out, show user list of available GPIB addresses. Then exit
  print("Connection to Solartron timed out. Check GBIB address is correct and try
      again.")
  print("Available GPIB resources are: ")
  print(resources)
  quit()

sol.timeout = int(1000000000)

# For use with Voltage mode
VAMPL = 3.0
VBIAS = 0.996

# For use with Current mode
IAMPL = 0.05
IBIAS = 0.0

# We are now connected to the Solartron. Setup the manual sweep parameters
```

```
# Using generator and single measurements, NOT the built-in sweep function of the
    Solartron
send('TT2 ')          # Reset time. sleep (3)
#time.sleep(3)
#send('TT1 ')         # Initialized.
input("Press Enter to start sweep...")
send('OS 0')          # GPIB seperator 'comma '
send('OT 0')          # GPIB terminator 'cr lf '
send('OP 2 ,1')       # Set GPIB to 'dump all '
send('CZ 1')          # Display Z coordinates 'Z, theta '
send('UW 1')          # Display phase 'unwrapped '
#send('CC 1')         # Set circuit type being measured **
send('IP 1 ,1 ')        # Set Input V1 : input to ' differential '
send('OU 1 ,0 ')        # Set Input V1 : outer to 'grounded '
send('IP 2 ,1 ')        # Set Input V2 : input to ' differential '
send('OU 2 ,0 ')        # Set Input V2 : outer to 'grounded '
send('GT 1')          # Voltage or Current mode (0 or 1) NOTE: make sure this is
    correct mode or you will not get a stimulus signal
#send('VB ' + str(VBIAS))          # Sweep voltage bias
#send('VA ' + str(VAMPL))          # Sweep voltage amplitude
send('IB ' + str(IBIAS))           # Sweep current bias
send('IA ' + str(IAMPL))           # Sweep current amplitude
send('DC 1 ,0 ')        # Set V1 coupling to DC
send('DC 3 ,0 ')        # Set I coupling to DC
send('RA 1 ,0 ')        # Set voltage range to 'auto '
send('RA 3 ,0 ')        # Set current range to 'auto '

# Begin sweep. Set frequency for each sample point, run single measurement, and
    retrieve result
print("Started manual sweep...")
print(" Freq \t\tZ( Ohms ) \tPhase ( deg )")


#list = [10.0, 5.0, 2.0, 1.0, 0.5, 0.2, 0.1, 50e-3, 20e-3, 10e-3]
list = [5.0, 2.0, 1.0, 0.5, 0.2, 0.1, 50e-3, 20e-3, 10e-3, 5e-3, 2e-3, 1e-3, 500e-6,
    200e-6, 100e-6, 50e-6, 20e-6, 10e-6]
#list = [5.0, 2.0, 1.0, 0.5, 0.2, 0.1, 50e-3, 20e-3, 10e-3, 5e-3, 2e-3, 1e-3, 500e-6,
     200e-6, 100e-6, 50e-6, 30e-6]
#list = [1000000.0, 500000.0, 200000.0, 100000.0, 50000.0, 20000.0, 10000.0, 5000.0,
    2000.0, 1000.0, 500.0, 200.0, 100.0, 50.0, 20.0, 10.0, 5.0, 2.0, 1.0]
#list = [5.0, 2.0, 1.0]

f = open(datetime.now().strftime("%Y_%m_%d-%I_%M_%S_%p") + ".fmp","w+")

for x in list:
        if x >= 1e-3:
                send('IS ' + str(max(5, 6/x)))    # Set integration time (6 cycles)
        else:
                send('IS 1')        # Set integration time (1 Cycle)
        send('FR ' + str(x))                    # Set generator frequency
        start_measure = sol.query('SI')   # Start measurement and wait for it to
            finish (when query returns)
        send('SO 1 ,3 ')        # Set Display source to 'Z1=V1/I' to convert last
            measurement to Z, theta
        result = sol.query('DO ').split(',')    # Request last measurement again. It
             is now in form "freq, Z, theta"
        # Extract numbers from received data
        actualFreq = result[0]
        Z = result[1]
        phase = result[2]
        print(str(actualFreq) + '\t' + str(Z) + '\t' + str(phase))
        f.write(str(actualFreq) + '\t' + str(Z) + '\t' + str(phase)+ '\n')

print("Sweep complete.")
f.close()
```

B.2 DFT Implementation

Listing B.2: DFT implementation header file

```
#ifndef DFT_H
#define DFT_H

#ifdef __cplusplus
extern "C" {
#endif

#include <stdint.h>
#include <stdbool.h>

typedef enum
{
    kDftIdle = 0,
    kDftWaitPrompt,
    kDftSetup,
    kDftRunning,
    kDftFinished,
} DftState;

typedef enum
{
    kDftErrMsgNone = 0,
    kDftErrMsgDischarged,
    kDftErrMsgDeltaV,
    kDftErrMsgSdCard,
} DftErrorMsg;

// NOTE: Called in the IRQ handler declared in stm32f4xx_it.c
void DFT_TimerHandler();

uint64_t DFT_GetTimeSeconds();

void DFT_SetRunFlag(bool flag);

bool DFT_GetRunFlag();

void DFT_SetVoltage(float voltage);

void DFT_SetCurrent(float current);

float DFT_GetVoltage();

float DFT_GetCurrent();

void DFT_Init();

void DFT_DumpFmpToTerminal();

void DFT_Task();

#ifdef __cplusplus
}
#endif

#endif /* DFT_H */
```

Listing B.3: DFT implementation source file

```
#include "DFT.h"

#include <string.h>
#include <stdio.h>
```

```c
#include <stdlib.h>
#include <math.h>

#include "custom_printf.h"
#include "tm_stm32_general.h"
#include "stm32f4xx_hal_tim.h"
#include "stm32f4xx_hal_tim_ex.h"
#include "tm_stm32_delay.h"

#include "Config.h"
#include "Watchdog.h"
#include "DEV_Config.h"
#include "DAC8532.h"
#include "ADS1256.h"
#include "Buttons.h"
#include "Analyzer.h"
#include "Display.h"
#include "SDCard.h"

#if (1)
#define DFT_LOG(__info,...)      custom_printf("DFT_LOG: " __info,##__VA_ARGS__)
#else
#define DFT_LOG(__info,...)
#endif

#define DFT_TIMER                TIM4
#define DFT_TIMER_IRQn           TIM4_IRQn
#define DFT_TIMER_PRESCALER      (14)

/* Set for 10ms Interrupts */
#define DFT_TIMER_FREQ_HZ        (100)

static TIM_HandleTypeDef dftTimHandle;

// INA250A4 precision current sensor gain value in V/A (in Volts per Amp)
#define INA250A4_GAIN            (2.0)

// these are set at compile time for each application
#define IBIAS                    (0.1)           // Used to add a DC offset. Set to
    zero if measuring batteries and supercapacitors
//#define NOMMV                  (3000.0)    // nominal cell voltage
#define VERROR                   (0.0)           // the "flat" voltage value
#define NF                       (6)           // number of tones
#define NCYCLES                  (6)       // number of cycles of lowest frequency

#define PERIOD1 100000L                         // number of 10ms periods in PERIOD of
     lowest frequency
static const double freq[NF] = {1e-3, 2e-3, 5e-3, 10e-3, 20e-3, 50e-3}; //6 tones

//#define PERIOD1 1000000L                         // number of 10ms periods in PERIOD
     of lowest frequency
//static const double freq[NF] = {100e-6, 200e-6, 500e-6, 1e-3, 2e-3, 5e-3, 10e-3, 20
    e-3, 50e-3, 0.1, 0.2, 0.5, 1.0, 2.0}; //14 tones

//#define PERIOD1 10000000L                        // number of 10ms periods in PERIOD
     of lowest frequency
//static const double freq[NF] = {10e-6, 20e-6, 50e-6, 100e-6, 200e-6, 500e-6, 1e-3,
    2e-3, 5e-3, 10e-3, 20e-3, 50e-3, 0.1, 0.2, 0.5, 1.0}; //16 tones

static double freqMin;
static double freqMax;
static const double currentMax = 0.05;
static const double chargeMax = 0.05;
static double dQMax = 0;
static double freqMaxCurrent[NF] = {0};

// globals, access in ISR and main
static uint64_t t10ms; // time since start in multiples of 10ms
```

```
static uint64_t t1sec; // 1 sec ticks
static uint64_t tRemaining;
static bool bUpdateDisplay = false;
static uint8_t cycle; // progress in cycle number
static double Vmin = 4.2; // low Vb limit
static double Vmax = 0.0; // hi Vb limit
static uint8_t badvoltage = 0; // battery went flat?
static bool sync; // ISR sync flag
static uint64_t nseq = -1; // counts samples
static uint64_t tstamp, prevtstamp; // measurement timestamp
static uint64_t tmodulo; // measurement time, modulo LCM period
static double VbV, prevVb; // supply in volts
static double IbA, prevIb; // load current amps
static double dtmp, dtmp2;
static double win; // phase/value of raised cosine window
static double Zmag[NF], Zpha[NF]; // the target outputs
static double ReVsum[NF], ImVsum[NF]; // running sums in real & imaginary
static double ReIsum[NF], ImIsum[NF]; // running sums in real & imaginary
static double Vbwin, Ibwin; // I and V values, windowed
static double prevVbwin, prevIbwin; // previous I and V values, windowed
static double sumOfSines; // generator value

static float dataIn[4];
static bool _bRun = false;
static char _buffer[256];
static char _tviFilename[256];
static char _fmpFilename[256];
static int32_t runCounter;

static DftState dftState = kDftWaitPrompt;
static DftErrorMsg dftErrMsg = kDftErrMsgNone;

#define DFT_RUNDIAGNOSTICS       (0)

static void DFT_Integrate(double* Rsum, double* Isum, uint8_t i, uint64_t tn,
    uint64_t tnm1, double yn, double ynm1)
{
    double kay, ang, slope, thiscos, thissin, lsin, lcos;

    kay = (tn - tnm1) / 100.00;
    slope = (yn - ynm1) / kay;

    kay = M_TWOPI * freq[i];
    ang = kay * tnm1 / 100.0; // convert time into seconds
    lcos = cos(ang);
    lsin = sin(ang);
    ang = kay * tn / 100.0; // convert tn into seconds from j*10ms
    thiscos = cos(ang);
    thissin = sin(ang);

    Isum[i] += slope * (thissin - lsin) / (kay * kay);
    Isum[i] -= (yn * thiscos - ynm1 * lcos) / kay;
    Rsum[i] += slope * (thiscos - lcos) / (kay * kay);
    Rsum[i] += (yn * thissin - ynm1 * lsin) / kay;

}

/* from Scott & Parker 1995
        lsin = sin(0.0);
        lcos = cos(0.0);
        kay = TWOPI * j * fundamental;
        for(i=1; i<ndatl; i++) {
            ang = (xjbs[i]-xjbs[0])*kay;
            width = xjbs[i]-xjbs[i-1];
            slope = (yjbs[i]-yjbs[i-1])/width;
            thiscos = cos(ang);
            thissin = sin(ang);
            imag += slope*(thissin-lsin)/(kay*kay);
```

```
            imag -= (yjbs[i]*thiscos-yjbs[i-1]*lcos)/kay;
            real += slope*(thiscos-lcos)/(kay*kay);
            real += (yjbs[i]*thissin-yjbs[i-1]*lsin)/kay;
            lsin = thissin;
            lcos = thiscos;
            }

            Bhaskara's Sine approximation
            sin(x) ~ 16x(pi-x)/(5pi^2-4x(pi-x)) 0<x<pi error <1.5% (2 *, 1 /)
            error for 7th-order poly is 3ppm, so error <.0003% (10 *)
            sin(x) ~ x-x^3/3!+x^5/5!-x^7/7!
            arctan(x) ~ see Rajan etal., Efficient Approximations for the Arctangent
                Function

 */

void DFT_TimerHandler()
{
    t10ms += 1; // increment time in 10ms intervals
    if(t10ms % DFT_TIMER_FREQ_HZ == 0)
    {
        t1sec++;
        bUpdateDisplay = true;
    }

    sync = 1;   // ISR running

    // "Resets" interrupt flag etc
    DFT_TIMER->SR = ~TIM_IT_UPDATE;
}

static uint32_t DFT_CalcPeriod(uint32_t freq, uint32_t prescaler)
{
    /* TIMCLK = 90 MHz, Freq = TIMCLK / ((Prescaler + 1)*(Period + 1))
       NOTE: 16bit limited */
    return ((90000000 / freq)/(prescaler + 1)) - 1;
}

static bool DFT_TimerInit()
{
    __HAL_RCC_TIM4_CLK_ENABLE();
    dftTimHandle.Instance = DFT_TIMER;
    uint32_t period = DFT_CalcPeriod(DFT_TIMER_FREQ_HZ, DFT_TIMER_PRESCALER);
    dftTimHandle.Init.Period = period;
    dftTimHandle.Init.Prescaler = DFT_TIMER_PRESCALER;
    dftTimHandle.Init.ClockDivision = TIM_CLOCKDIVISION_DIV1;
    dftTimHandle.Init.CounterMode = TIM_COUNTERMODE_UP;

    HAL_StatusTypeDef status = HAL_TIM_Base_Init(&dftTimHandle);
    if (status != HAL_OK)
        return false;

    HAL_NVIC_EnableIRQ(DFT_TIMER_IRQn);
    HAL_NVIC_SetPriority(DFT_TIMER_IRQn, 3, 3);

    return true;
}

static bool DFT_TimerStart()
{
    HAL_StatusTypeDef status = HAL_TIM_Base_Start_IT(&dftTimHandle);
    if (status != HAL_OK)
        return false;
    return true;
}

static bool DFT_TimerStop()
{
```

```
    HAL_StatusTypeDef status = HAL_TIM_Base_Stop_IT(&dftTimHandle);
    if (status != HAL_OK)
        return false;
    return true;
}

static void DFT_AdcScan()
{
    // Scan all channels
    for(uint8_t i = 0; i < 4; i++)
    {
        dataIn[i] = (float)(ADS1256_GetChannelValue(i) * 5.0 / 0x7fffff);
    }
}

uint64_t DFT_GetTimeSeconds()
{
    return t1sec;
}

void DFT_SetVoltage(float voltage)
{
    DAC8532_OutVoltage(channel_A, voltage);
    DAC8532_OutVoltage(channel_B, voltage);
}

void DFT_SetCurrent(float current)
{
    // Gain of VCCS (Voltage controlled current source) is 2.5V
    float voltage = ((current - 0.0037) * 2.5) + 2.5; // VOUT = ((ILOAD - VCCS_TRIM)
        * GAIN) + VREF
    DFT_SetVoltage(voltage);
}

float DFT_GetVoltage()
{
    //return dataIn[3] / (56.0 / (300.0 + 56.0)); // 150kOhm parallel with input
        impedance of ADC is 56kOhm
    return dataIn[2];
}

float DFT_GetCurrent()
{
    return ((dataIn[1] - 2.5) / 2.0) + 0.01; // ILOAD = ((VOUT - VREF) / GAIN) +
        INA250_OFFSET
}

void DFT_SetRunFlag(bool flag)
{
    _bRun = flag;
}

bool DFT_GetRunFlag()
{
    return _bRun;
}

void DFT_Init()
{
  ADS1256_Init();
  /* NOTE: For single-ended measurements, use AINCOM (Analog input common) as common
      input, which
  can be connected to AGND or external reference voltage (via JMP_AGND). For
      differential measurements, do not
  use AINCOM. */
  ADS1256_SetMode(1); // Set to differential scan mode

    TM_GPIO_Init(GPIOA, GPIO_PIN_11, TM_GPIO_Mode_IN, TM_GPIO_OType_OD,
```

```
        TM_GPIO_PuPd_NOPULL, TM_GPIO_Speed_High);

    DFT_TimerInit();
    DFT_TimerStart();
}

static void DFT_CheckVoltageLimits()
{
    if (VbV < Vmin)
        Vmin = VbV;
    if (VbV > Vmax)
        Vmax = VbV;

    if (VbV < VERROR)
    {
        DFT_LOG("Bad Voltage (discharged)\r\n");
        badvoltage = 1; // flat error
        dftState = kDftFinished; // exit early
    }

    if (Vmax - Vmin > 0.25)
    {
        DFT_LOG("Bad Voltage (deltaV)\r\n");
        badvoltage = 2; // deltaV error
        dftState = kDftFinished; // exit early
    }
}

static void DFT_FindMaxCurrents()
{
    freqMin = fabs(freq[0]);
    freqMax = fabs(freq[0]);

    /* Find highest and lowest frequencies given */
    uint8_t nfrequencies = 1;

    for(uint8_t i = 1; i < NF; i++)
    {
        if(freq[i] != 0.0f)
        {
            if(fabs(freq[i]) < freqMin)
            {
                freqMin = fabs(freq[i]);
                if (freqMin < 0.0f)
                    DFT_LOG("freqMin less than zero: %f\r\n", freqMin);
            }
            if(fabs(freq[i]) > freqMax)
            {
                freqMax = fabs(freq[i]);
            }
            nfrequencies++;
        }
        else
            break;
    }
    DFT_LOG("Lowest Frequency: %f\r\n", freqMin);

    /* What q will be moved by the slowest frequency in Ah */
    dQMax = currentMax / (M_PI * freqMin * 3600);
    if (fabs(chargeMax) < fabs(dQMax))
    {
        dQMax = chargeMax;
    }

    DFT_LOG("Given QMax: %g\r\n", chargeMax);
    DFT_LOG("dQ: %g\r\n", dQMax);
    DFT_LOG("\r\n");
```

```c
    for(uint8_t i = 0; i < nfrequencies; i++)
    {
        // divide amplitude of each sine wave to produce equal charge movement for
            each
        // dQ_f = -2*nfreq*I_f/(2*pi*f)
        // dI_f = Q_f*(2*pi*f)/2*nfreq
        // dI_f = Q_f*(pi*f)/nfreq
        freqMaxCurrent[i] = fabs(dQMax * M_PI * freq[i] * 3600 / (double)nfrequencies
            );
        if(fabs(freqMaxCurrent[i]) > fabs(currentMax / nfrequencies))
        {
            freqMaxCurrent[i] = currentMax / nfrequencies;
        }

        DFT_LOG("Maximum current for frequency %e Hz: %e A\r\n", freq[i],
            freqMaxCurrent[i]);
    }
}

static void DFT_ZeroizeArrays()
{
    for (uint8_t i = 0; i < NF; i++)
    { // for each frequency
        Zmag[i] = 0.0; // zero the data
        Zpha[i] = 0.0;
    }
}

static void DFT_CalculateTimeRemaining()
{
    // Set time remaining in seconds
    double tlowestperiod = (1.0 / freqMin) * (double)NCYCLES;
    tRemaining = (uint64_t)tlowestperiod;
}

static void DFT_PrintErrorMessage(DftErrorMsg errMsg)
{

    _buffer[0] = '\0';

    switch(errMsg)
    {
        case kDftErrMsgNone:
        {
            sprintf(_buffer, "Err:None\n");
        }
            break;
        case kDftErrMsgDischarged:
        {
            sprintf(_buffer, "Err:Discharged\n");
        }
            break;
        case kDftErrMsgDeltaV:
        {
            sprintf(_buffer, "Err:Delta V\n");
        }
            break;
        case kDftErrMsgSdCard:
        {
            sprintf(_buffer, "Err:SD Card\n");
        }
            break;
        default:
            break;
    }

    Display_Puts(10, 150, _buffer);
}
```

```
static void DFT_UpdateDisplay()
{
    if(bUpdateDisplay)
    {
        if(dftState == kDftIdle)
        {

#if DFT_RUNDIAGNOSTICS
            DFT_SetCurrent(0.1); // Set a constant current for diagnostic purposes
            if(_bRun)
            {
                Analyzer_SetRelay(0);
                Analyzer_SetRelay(1);
                Delayms(1000); // wait for relays to settle
                _bRun = false;
            }
#endif
            DFT_AdcScan();

            _buffer[0] = '\0';
            sprintf(_buffer, "V:%+9.6fV\n", DFT_GetVoltage());
            sprintf(_buffer, "%-19s", _buffer); //right padding
            Display_Puts(10, 80, _buffer);
            _buffer[0] = '\0';
            sprintf(_buffer, "I:%+9.6fA\n", DFT_GetCurrent());
            sprintf(_buffer, "%-19s", _buffer); //right padding
            Display_Puts(10, 115, _buffer);
        }
        else
        {
            _buffer[0] = '\0';
            sprintf(_buffer, "Cycle:%d", (unsigned int)cycle);
            Display_Puts(10, 10, _buffer);
            _buffer[0] = '\0';
            sprintf(_buffer, "tRem:%ds", (unsigned int)tRemaining);
            sprintf(_buffer, "%-19s", _buffer); //right padding
            Display_Puts(10, 45, _buffer);
            _buffer[0] = '\0';
            sprintf(_buffer, "V:%+9.6fV\n", DFT_GetVoltage());
            sprintf(_buffer, "%-19s", _buffer); //right padding
            Display_Puts(10, 80, _buffer);
            _buffer[0] = '\0';
            sprintf(_buffer, "I:%+9.6fA\n", DFT_GetCurrent());
            sprintf(_buffer, "%-19s", _buffer); //right padding
            Display_Puts(10, 115, _buffer);

            if(badvoltage == 1)
                dftErrMsg = kDftErrMsgDischarged;
            else if(badvoltage == 2)
                dftErrMsg = kDftErrMsgDeltaV;
            else if(SDCard_CheckError())
                dftErrMsg = kDftErrMsgSdCard;

            DFT_PrintErrorMessage(dftErrMsg);

            //DFT_LOG("Cycle:%d, tRem:%ds, V:%+9.6fV, I:%+9.6fA,\r\n", (unsigned int)
                cycle, (unsigned int)tRemaining, DFT_GetVoltage(), DFT_GetCurrent());
            tRemaining--;
            if(tRemaining < 0)
                tRemaining = 0;
        }
        bUpdateDisplay = false;
    }
}

void DFT_DumpFmpToTerminal()
{
```

```
    DFT_LOG(".fmp Dump:\r\n\r\n");
    for (uint8_t i = 0; i < NF; i++)
    {
        custom_printf("%+1.6e %+1.6e %+1.6e\r\n", freq[i], Zmag[i],  Zpha[i]);
    }
    custom_printf("\r\n");
}

void DFT_Task()
{
    switch(dftState)
    {
        case kDftIdle:
        {
            Watchdog_Kick();
            Buttons_Task();
            DFT_UpdateDisplay();
#if !DFT_RUNDIAGNOSTICS
            if(_bRun)
               dftState = kDftSetup;
#endif
        }
            break;
        case kDftWaitPrompt:
        {
            DFT_LOG("Waiting for user...\r\n");
            Display_Puts(10, 10, "Waiting for user...");
            dftState = kDftIdle;
        }
            break;
        case kDftSetup:
        {
            Display_ClearScreen();
            DFT_LOG("Setting up...\r\n");
            Display_Puts(10, 10, "Setting up...      ");
            Delayms(1000);

            DFT_FindMaxCurrents();
            DFT_ZeroizeArrays();

            DFT_LOG("DFT setup complete.\r\n");
            Display_Puts(10, 10, "DFT setup complete.");
            DFT_SetCurrent(0.0 + IBIAS); // Make sure current is zero
            Analyzer_SetRelay(0);
            Analyzer_SetRelay(1);
            Delayms(1000); // wait for relays to settle

            DFT_CalculateTimeRemaining();

            dftState = kDftRunning;
        }
            break;
        case kDftRunning:
        {
            DFT_LOG("DFT running...\r\n");

            SDCard_Mount();
            SDCard_GetCardInfo();

            _tviFilename[0] = '\0';
            sprintf(_tviFilename, "log_%d.tvi", (unsigned int)runCounter);
            SDCard_FileOpen(_tviFilename);
            DFT_LOG("Created file: %s\r\n", _tviFilename);

            Display_ClearScreen();
            t1sec = 0;
//            DFT_TimerStop();
//            Delayms(100);
```

```
//              DFT_AdcScan();
//              DFT_TimerStart();
            t10ms = 0L;
            while(1)
            {
                nseq++; // count points measured
                sync = 0; // clear ISR sync flag
                while (!sync)
                {
                    ;
                } // wait until time is multiple of ISR rate

                TM_GENERAL_DisableInterrupts();
                tstamp = t10ms;
                TM_GENERAL_EnableInterrupts(); // atomic grab of timestamp

                DFT_AdcScan(); // Scan all channels

                prevVb = VbV; // current to previous value
                VbV = (double) DFT_GetVoltage();

                DFT_CheckVoltageLimits();

                prevIb = IbA; // store previous
                IbA = (double) DFT_GetCurrent();

                // log to .tvi file
                _buffer[0] = '\0';
                sprintf(_buffer, "%f\t%.8f\t%.8f\n", (double)tstamp / 100.0, VbV, IbA
                    );
                SDCard_FilePuts(_buffer);

                // preserve precision by using modulo time in trig calculations
                tmodulo = tstamp;
                cycle = 1; // at least in 1st cycle

                while (tmodulo >= PERIOD1)
                {
                    tmodulo -= PERIOD1; // signal periodic in PERIOD1
                    cycle++; // what cycle we are in
                }

                // update current drive
                dtmp2 = (10e-3 * M_TWOPI) * tmodulo; // 2.pi.t

                sumOfSines = 0.0;
                for (uint8_t i = 0; i < NF; i++)
                { // for each tone
                    dtmp = dtmp2 * freq[i]; // 2*pi*f*t
                    //sumOfSines += (freqMaxCurrent[i] * sin(dtmp + NF)); // sum of
                        sin(2.pi.f.t+phase)
                    sumOfSines += (freqMaxCurrent[i] * sin(dtmp)); // sum of sin(2.pi
                        .f.t+phase)
                } // adding NF phase randomises

                DFT_SetCurrent((float) sumOfSines + IBIAS);

                // integrate each Fourier segment
                if (tstamp > (PERIOD1 * NCYCLES))
                { // gone past the end
                    // integrate last chunk
                    tstamp = (PERIOD1); // about to clear this var anyway
                    for (uint8_t i = 0; i < NF; i++)
                    {
                        DFT_Integrate(ReVsum, ImVsum, i, tstamp, prevtstamp, 0.00,
                            prevVbwin);
                        DFT_Integrate(ReIsum, ImIsum, i, tstamp, prevtstamp, 0.00,
                            prevIbwin);
```

```
        }

        for (uint8_t i = 0; i < NF; i++)
        { // output wanted data
            dtmp = (ReVsum[i] * ReVsum[i]);
            dtmp += (ImVsum[i] * ImVsum[i]);
            dtmp2 = sqrt(dtmp); // sqrt(Re^2+Im^2), Voltage
            dtmp = (ReIsum[i] * ReIsum[i]);
            dtmp += (ImIsum[i] * ImIsum[i]);
            dtmp = sqrt(dtmp); // sqrt(Re^2+Im^2), Current
            Zmag[i] = dtmp2 / dtmp; // |Z| in "V/A"
            dtmp = atan2(ImVsum[i], ReVsum[i]);
            dtmp -= atan2(ImIsum[i], ReIsum[i]); // dtmp is phase
                difference in radians
            dtmp /= M_TWOPI;
            dtmp *= 360.0; // arg(Z) in degrees
            while (dtmp < 0.0)
                dtmp += 360.0; // range 0->360
            Zpha[i] = -dtmp; // arg(Z) in degrees, negative for
                convention
        }

        //DFT_TimerStop();

        SDCard_FileClose(); // Close .tvi file

        // log to .fmp file
        _fmpFilename[0] = '\0';
        sprintf(_fmpFilename, "log_%d.fmp", (unsigned int)runCounter);
        SDCard_FileOpen(_fmpFilename);
        DFT_LOG("Created file: %s\r\n", _fmpFilename);

        DFT_DumpFmpToTerminal();

        for (uint8_t i = 0; i < NF; i++)
        {
            _buffer[0] = '\0';
            sprintf(_buffer, "%+1.6e\t%+1.6e\t%+1.6e\n", freq[i], Zmag[i
                ], Zpha[i]);
            SDCard_FilePuts(_buffer);
        }

        SDCard_FileClose(); // Close .fmp file
        SDCard_Unmount();

        runCounter++; // Increment run counter for next time through

        nseq = 0; // clear points
        badvoltage = 0;
        tRemaining = 0;
        dftState = kDftFinished;
    }

    if (nseq == 0)
    { // start, first point
        TM_GENERAL_DisableInterrupts();
        t10ms = 0L;
        TM_GENERAL_EnableInterrupts(); // clear master time
        tstamp = prevtstamp = 0; // clear timestamps
        prevVbwin = 0.00; // set previous values...
        prevIbwin = 0.00; // zero at edge of Hann window
        for (uint8_t i = 0; i < NF; i++)
        { // for each tone
            ReVsum[i] = 0.00; // clear integration accumulators
            ReIsum[i] = 0.00;
            ImVsum[i] = 0.00;
            ImIsum[i] = 0.00;
        }
```

```
                }
                else
                { // this is where most work is done
                    // compute Hann window multiplier, across whole duration, PERIOD1
                        *NCYCLES
                    win = (double) tstamp / (PERIOD1 * NCYCLES);
                    win *= M_TWOPI; // 0 to 2pi
                    win = 1.00 - cos(win); // Hann raised cosine
                    prevVbwin = Vbwin; // keep previous, already windowed
                    prevIbwin = Ibwin;
                    Vbwin = VbV * win;
                    Ibwin = IbA * win;
                    // offset around zero reduces large values in float accumulators
                    // now we have 2 windowed tvi data, prev & new, for I & V, at NF
                        frequencies
                    for (uint8_t i = 0; i < NF; i++)
                    { // for each tone
                        DFT_Integrate(ReVsum, ImVsum, i, tmodulo, prevtstamp, Vbwin,
                            prevVbwin);
                        DFT_Integrate(ReIsum, ImIsum, i, tmodulo, prevtstamp, Ibwin,
                            prevIbwin);
                    } // have now integrated across one slice of the V & I waveforms
                    prevtstamp = tmodulo; // keep last x-point for next time
                }

                // handle low prio tasks
                Watchdog_Kick();
                Buttons_Task();
                DFT_UpdateDisplay();

                // Check to see if run is finished
                if(dftState == kDftFinished)
                    break;
            }
        }
            break;
        case kDftFinished:
        {
            Display_ClearScreen();
            DFT_LOG("Run complete.\r\n");
            Display_Puts(10, 10, "Run complete.        ");
            _bRun = false;
            Analyzer_ClearRelay(0);
            Analyzer_ClearRelay(1);
            Delayms(1000);
            Display_ClearScreen();
            dftState = kDftWaitPrompt;
        }
            break;
        default:
            break;
    }
}
```

B.3 CPE SPICE Netlist

Listing B.4: SPICE Netlist for CPE Model

```
Test CPE
* f0 = 3.0 Hz
* fstart = 3e-05 Hz
* fstop = 10.0 Hz
* kf = 1.1
* alpha = 0.9757
```

```
* magZ = 0.04 Ohms
******************************
Vs 1 0 ac 1 dc 0
Rs 1 2 0.078
X1 2 0 CPE
******************************
.subckt CPE n1 n2
* Tau 0.0530516 s, freq     3 Hz
Rcpe0 n1 internalNode0 3.05533
Ccpe0 n2 internalNode0 0.0173636
* Tau 0.0584921 s, freq 2.72096 Hz
Rcpe1 n1 internalNode1 3.36087
Ccpe1 n2 internalNode1 0.0174039
* Tau 0.0644905 s, freq 2.46788 Hz
Rcpe2 n1 internalNode2 3.69695
Ccpe2 n2 internalNode2 0.0174442
* Tau 0.0711041 s, freq 2.23834 Hz
Rcpe3 n1 internalNode3 4.06665
Ccpe3 n2 internalNode3 0.0174847
* Tau 0.0783958 s, freq 2.03015 Hz
Rcpe4 n1 internalNode4 4.47331
Ccpe4 n2 internalNode4 0.0175252
* Tau 0.0864354 s, freq 1.84132 Hz
Rcpe5 n1 internalNode5 4.92065
Ccpe5 n2 internalNode5 0.0175659
* Tau 0.0952994 s, freq 1.67005 Hz
Rcpe6 n1 internalNode6 5.41271
Ccpe6 n2 internalNode6 0.0176066
* Tau 0.105072 s, freq 1.51472 Hz
Rcpe7 n1 internalNode7 5.95398
Ccpe7 n2 internalNode7 0.0176474
* Tau 0.115848 s, freq 1.37383 Hz
Rcpe8 n1 internalNode8 6.54938
Ccpe8 n2 internalNode8 0.0176883
* Tau 0.127728 s, freq 1.24605 Hz
Rcpe9 n1 internalNode9 7.20432
Ccpe9 n2 internalNode9 0.0177293
* Tau 0.140826 s, freq 1.13015 Hz
Rcpe10 n1 internalNode10 7.92475
Ccpe10 n2 internalNode10 0.0177705
* Tau 0.155268 s, freq 1.02503 Hz
Rcpe11 n1 internalNode11 8.71723
Ccpe11 n2 internalNode11 0.0178117
* Tau 0.171191 s, freq 0.929692 Hz
Rcpe12 n1 internalNode12 9.58895
Ccpe12 n2 internalNode12 0.017853
* Tau 0.188747 s, freq 0.843219 Hz
Rcpe13 n1 internalNode13 10.5478
Ccpe13 n2 internalNode13 0.0178944
* Tau 0.208103 s, freq 0.764789 Hz
Rcpe14 n1 internalNode14 11.6026
Ccpe14 n2 internalNode14 0.0179358
* Tau 0.229444 s, freq 0.693655 Hz
Rcpe15 n1 internalNode15 12.7629
Ccpe15 n2 internalNode15 0.0179774
* Tau 0.252974 s, freq 0.629136 Hz
Rcpe16 n1 internalNode16 14.0392
Ccpe16 n2 internalNode16 0.0180191
* Tau 0.278916 s, freq 0.570619 Hz
Rcpe17 n1 internalNode17 15.4431
Ccpe17 n2 internalNode17 0.0180609
* Tau 0.307519 s, freq 0.517545 Hz
Rcpe18 n1 internalNode18 16.9874
Ccpe18 n2 internalNode18 0.0181028
* Tau 0.339056 s, freq 0.469407 Hz
Rcpe19 n1 internalNode19 18.6861
Ccpe19 n2 internalNode19 0.0181448
* Tau 0.373826 s, freq 0.425746 Hz
```

```
Rcpe20 n1 internalNode20 20.5548
Ccpe20 n2 internalNode20 0.0181868
* Tau 0.412162 s, freq 0.386147 Hz
Rcpe21 n1 internalNode21 22.6102
Ccpe21 n2 internalNode21 0.018229
* Tau 0.454429 s, freq 0.35023 Hz
Rcpe22 n1 internalNode22 24.8713
Ccpe22 n2 internalNode22 0.0182713
* Tau 0.501031 s, freq 0.317655 Hz
Rcpe23 n1 internalNode23 27.3584
Ccpe23 n2 internalNode23 0.0183136
* Tau 0.552413 s, freq 0.288109 Hz
Rcpe24 n1 internalNode24 30.0942
Ccpe24 n2 internalNode24 0.0183561
* Tau 0.609063 s, freq 0.261311 Hz
Rcpe25 n1 internalNode25 33.1036
Ccpe25 n2 internalNode25 0.0183987
* Tau 0.671523 s, freq 0.237006 Hz
Rcpe26 n1 internalNode26 36.414
Ccpe26 n2 internalNode26 0.0184413
* Tau 0.740388 s, freq 0.214962 Hz
Rcpe27 n1 internalNode27 40.0554
Ccpe27 n2 internalNode27 0.0184841
* Tau 0.816315 s, freq 0.194968 Hz
Rcpe28 n1 internalNode28 44.061
Ccpe28 n2 internalNode28 0.0185269
* Tau 0.900028 s, freq 0.176833 Hz
Rcpe29 n1 internalNode29 48.4671
Ccpe29 n2 internalNode29 0.0185699
* Tau 0.992327 s, freq 0.160386 Hz
Rcpe30 n1 internalNode30 53.3138
Ccpe30 n2 internalNode30 0.018613
* Tau 1.09409 s, freq 0.145468 Hz
Rcpe31 n1 internalNode31 58.6451
Ccpe31 n2 internalNode31 0.0186561
* Tau 1.20629 s, freq 0.131938 Hz
Rcpe32 n1 internalNode32 64.5096
Ccpe32 n2 internalNode32 0.0186994
* Tau  1.33 s, freq 0.119666 Hz
Rcpe33 n1 internalNode33 70.9606
Ccpe33 n2 internalNode33 0.0187427
* Tau 1.46639 s, freq 0.108535 Hz
Rcpe34 n1 internalNode34 78.0567
Ccpe34 n2 internalNode34 0.0187862
* Tau 1.61677 s, freq 0.0984403 Hz
Rcpe35 n1 internalNode35 85.8623
Ccpe35 n2 internalNode35 0.0188298
* Tau 1.78257 s, freq 0.0892841 Hz
Rcpe36 n1 internalNode36 94.4486
Ccpe36 n2 internalNode36 0.0188734
* Tau 1.96537 s, freq 0.0809796 Hz
Rcpe37 n1 internalNode37 103.893
Ccpe37 n2 internalNode37 0.0189172
* Tau 2.16692 s, freq 0.0734475 Hz
Rcpe38 n1 internalNode38 114.283
Ccpe38 n2 internalNode38 0.018961
* Tau 2.38914 s, freq 0.066616 Hz
Rcpe39 n1 internalNode39 125.711
Ccpe39 n2 internalNode39 0.019005
* Tau 2.63415 s, freq 0.0604199 Hz
Rcpe40 n1 internalNode40 138.282
Ccpe40 n2 internalNode40 0.0190491
* Tau 2.90428 s, freq 0.0548001 Hz
Rcpe41 n1 internalNode41 152.11
Ccpe41 n2 internalNode41 0.0190932
* Tau 3.20212 s, freq 0.0497031 Hz
Rcpe42 n1 internalNode42 167.321
Ccpe42 n2 internalNode42 0.0191375
```

```
* Tau 3.53049 s, freq 0.0450801 Hz
Rcpe43 n1 internalNode43 184.054
Ccpe43 n2 internalNode43 0.0191819
* Tau 3.89255 s, freq 0.0408871 Hz
Rcpe44 n1 internalNode44 202.459
Ccpe44 n2 internalNode44 0.0192264
* Tau 4.29173 s, freq 0.0370841 Hz
Rcpe45 n1 internalNode45 222.705
Ccpe45 n2 internalNode45 0.0192709
* Tau 4.73185 s, freq 0.0336348 Hz
Rcpe46 n1 internalNode46 244.975
Ccpe46 n2 internalNode46 0.0193156
* Tau 5.21711 s, freq 0.0305064 Hz
Rcpe47 n1 internalNode47 269.473
Ccpe47 n2 internalNode47 0.0193604
* Tau 5.75212 s, freq 0.0276689 Hz
Rcpe48 n1 internalNode48 296.42
Ccpe48 n2 internalNode48 0.0194053
* Tau 6.34201 s, freq 0.0250954 Hz
Rcpe49 n1 internalNode49 326.062
Ccpe49 n2 internalNode49 0.0194503
* Tau 6.99238 s, freq 0.0227612 Hz
Rcpe50 n1 internalNode50 358.668
Ccpe50 n2 internalNode50 0.0194954
* Tau 7.70946 s, freq 0.0206441 Hz
Rcpe51 n1 internalNode51 394.535
Ccpe51 n2 internalNode51 0.0195406
* Tau 8.50007 s, freq 0.018724 Hz
Rcpe52 n1 internalNode52 433.989
Ccpe52 n2 internalNode52 0.0195859
* Tau 9.37175 s, freq 0.0169824 Hz
Rcpe53 n1 internalNode53 477.388
Ccpe53 n2 internalNode53 0.0196313
* Tau 10.3328 s, freq 0.0154028 Hz
Rcpe54 n1 internalNode54 525.126
Ccpe54 n2 internalNode54 0.0196769
* Tau 11.3925 s, freq 0.0139702 Hz
Rcpe55 n1 internalNode55 577.639
Ccpe55 n2 internalNode55 0.0197225
* Tau 12.5608 s, freq 0.0126708 Hz
Rcpe56 n1 internalNode56 635.403
Ccpe56 n2 internalNode56 0.0197682
* Tau 13.8489 s, freq 0.0114923 Hz
Rcpe57 n1 internalNode57 698.943
Ccpe57 n2 internalNode57 0.019814
* Tau 15.2691 s, freq 0.0104233 Hz
Rcpe58 n1 internalNode58 768.837
Ccpe58 n2 internalNode58 0.01986
* Tau 16.835 s, freq 0.00945384 Hz
Rcpe59 n1 internalNode59 845.721
Ccpe59 n2 internalNode59 0.019906
* Tau 18.5614 s, freq 0.00857452 Hz
Rcpe60 n1 internalNode60 930.293
Ccpe60 n2 internalNode60 0.0199522
* Tau 20.4649 s, freq 0.00777698 Hz
Rcpe61 n1 internalNode61 1023.32
Ccpe61 n2 internalNode61 0.0199985
* Tau 22.5636 s, freq 0.00705363 Hz
Rcpe62 n1 internalNode62 1125.65
Ccpe62 n2 internalNode62 0.0200448
* Tau 24.8775 s, freq 0.00639755 Hz
Rcpe63 n1 internalNode63 1238.22
Ccpe63 n2 internalNode63 0.0200913
* Tau 27.4287 s, freq 0.0058025 Hz
Rcpe64 n1 internalNode64 1362.04
Ccpe64 n2 internalNode64 0.0201379
* Tau 30.2415 s, freq 0.0052628 Hz
Rcpe65 n1 internalNode65 1498.25
```

```
Ccpe65 n2 internalNode65 0.0201846
* Tau 33.3428 s, freq 0.0047733 Hz
Rcpe66 n1 internalNode66 1648.07
Ccpe66 n2 internalNode66 0.0202314
* Tau 36.7621 s, freq 0.00432932 Hz
Rcpe67 n1 internalNode67 1812.88
Ccpe67 n2 internalNode67 0.0202783
* Tau 40.5321 s, freq 0.00392664 Hz
Rcpe68 n1 internalNode68 1994.17
Ccpe68 n2 internalNode68 0.0203253
* Tau 44.6887 s, freq 0.00356142 Hz
Rcpe69 n1 internalNode69 2193.58
Ccpe69 n2 internalNode69 0.0203725
* Tau 49.2715 s, freq 0.00323016 Hz
Rcpe70 n1 internalNode70 2412.94
Ccpe70 n2 internalNode70 0.0204197
* Tau 54.3243 s, freq 0.00292972 Hz
Rcpe71 n1 internalNode71 2654.24
Ccpe71 n2 internalNode71 0.020467
* Tau 59.8953 s, freq 0.00265722 Hz
Rcpe72 n1 internalNode72 2919.66
Ccpe72 n2 internalNode72 0.0205145
* Tau 66.0376 s, freq 0.00241006 Hz
Rcpe73 n1 internalNode73 3211.62
Ccpe73 n2 internalNode73 0.0205621
* Tau 72.8098 s, freq 0.0021859 Hz
Rcpe74 n1 internalNode74 3532.79
Ccpe74 n2 internalNode74 0.0206097
* Tau 80.2765 s, freq 0.00198258 Hz
Rcpe75 n1 internalNode75 3886.07
Ccpe75 n2 internalNode75 0.0206575
* Tau 88.5089 s, freq 0.00179818 Hz
Rcpe76 n1 internalNode76 4274.67
Ccpe76 n2 internalNode76 0.0207054
* Tau 97.5855 s, freq 0.00163093 Hz
Rcpe77 n1 internalNode77 4702.14
Ccpe77 n2 internalNode77 0.0207534
* Tau 107.593 s, freq 0.00147923 Hz
Rcpe78 n1 internalNode78 5172.35
Ccpe78 n2 internalNode78 0.0208016
* Tau 118.627 s, freq 0.00134164 Hz
Rcpe79 n1 internalNode79 5689.59
Ccpe79 n2 internalNode79 0.0208498
* Tau 130.792 s, freq 0.00121686 Hz
Rcpe80 n1 internalNode80 6258.55
Ccpe80 n2 internalNode80 0.0208981
* Tau 144.205 s, freq 0.00110367 Hz
Rcpe81 n1 internalNode81 6884.4
Ccpe81 n2 internalNode81 0.0209466
* Tau 158.993 s, freq 0.00100102 Hz
Rcpe82 n1 internalNode82 7572.84
Ccpe82 n2 internalNode82 0.0209952
* Tau 175.298 s, freq 0.000907911 Hz
Rcpe83 n1 internalNode83 8330.13
Ccpe83 n2 internalNode83 0.0210438
* Tau 193.275 s, freq 0.000823465 Hz
Rcpe84 n1 internalNode84 9163.14
Ccpe84 n2 internalNode84 0.0210926
* Tau 213.095 s, freq 0.000746872 Hz
Rcpe85 n1 internalNode85 10079.5
Ccpe85 n2 internalNode85 0.0211415
* Tau 234.948 s, freq 0.000677404 Hz
Rcpe86 n1 internalNode86 11087.4
Ccpe86 n2 internalNode86 0.0211906
* Tau 259.042 s, freq 0.000614397 Hz
Rcpe87 n1 internalNode87 12196.1
Ccpe87 n2 internalNode87 0.0212397
* Tau 285.607 s, freq 0.000557251 Hz
```

```
Rcpe88 n1 internalNode88 13415.8
Ccpe88 n2 internalNode88 0.021289
* Tau 314.896 s, freq 0.00050542 Hz
Rcpe89 n1 internalNode89 14757.3
Ccpe89 n2 internalNode89 0.0213383
* Tau 347.189 s, freq 0.00045841 Hz
Rcpe90 n1 internalNode90 16233.1
Ccpe90 n2 internalNode90 0.0213878
* Tau 382.794 s, freq 0.000415772 Hz
Rcpe91 n1 internalNode91 17856.4
Ccpe91 n2 internalNode91 0.0214374
* Tau 422.05 s, freq 0.0003771 Hz
Rcpe92 n1 internalNode92 19642
Ccpe92 n2 internalNode92 0.0214871
* Tau 465.331 s, freq 0.000342025 Hz
Rcpe93 n1 internalNode93 21606.2
Ccpe93 n2 internalNode93 0.0215369
* Tau 513.051 s, freq 0.000310213 Hz
Rcpe94 n1 internalNode94 23766.8
Ccpe94 n2 internalNode94 0.0215869
* Tau 565.665 s, freq 0.000281359 Hz
Rcpe95 n1 internalNode95 26143.5
Ccpe95 n2 internalNode95 0.0216369
* Tau 623.674 s, freq 0.000255189 Hz
Rcpe96 n1 internalNode96 28757.9
Ccpe96 n2 internalNode96 0.0216871
* Tau 687.632 s, freq 0.000231454 Hz
Rcpe97 n1 internalNode97 31633.6
Ccpe97 n2 internalNode97 0.0217374
* Tau 758.149 s, freq 0.000209926 Hz
Rcpe98 n1 internalNode98 34797
Ccpe98 n2 internalNode98 0.0217878
* Tau 835.898 s, freq 0.0001904 Hz
Rcpe99 n1 internalNode99 38276.7
Ccpe99 n2 internalNode99 0.0218383
* Tau 921.619 s, freq 0.000172691 Hz
Rcpe100 n1 internalNode100 42104.4
Ccpe100 n2 internalNode100 0.0218889
* Tau 1016.13 s, freq 0.000156628 Hz
Rcpe101 n1 internalNode101 46314.8
Ccpe101 n2 internalNode101 0.0219397
* Tau 1120.34 s, freq 0.00014206 Hz
Rcpe102 n1 internalNode102 50946.3
Ccpe102 n2 internalNode102 0.0219905
* Tau 1235.23 s, freq 0.000128847 Hz
Rcpe103 n1 internalNode103 56040.9
Ccpe103 n2 internalNode103 0.0220415
* Tau 1361.9 s, freq 0.000116862 Hz
Rcpe104 n1 internalNode104 61645
Ccpe104 n2 internalNode104 0.0220926
* Tau 1501.57 s, freq 0.000105993 Hz
Rcpe105 n1 internalNode105 67809.5
Ccpe105 n2 internalNode105 0.0221439
* Tau 1655.55 s, freq 9.61341e-05 Hz
Rcpe106 n1 internalNode106 74590.5
Ccpe106 n2 internalNode106 0.0221952
* Tau 1825.33 s, freq 8.71924e-05 Hz
Rcpe107 n1 internalNode107 82049.5
Ccpe107 n2 internalNode107 0.0222467
* Tau 2012.52 s, freq 7.90825e-05 Hz
Rcpe108 n1 internalNode108 90254.5
Ccpe108 n2 internalNode108 0.0222983
* Tau 2218.9 s, freq 7.17269e-05 Hz
Rcpe109 n1 internalNode109 99279.9
Ccpe109 n2 internalNode109 0.02235
* Tau 2446.45 s, freq 6.50554e-05 Hz
Rcpe110 n1 internalNode110 109208
Ccpe110 n2 internalNode110 0.0224018
```

```
* Tau 2697.34 s, freq 5.90044e-05 Hz
Rcpe111 n1 internalNode111 120129
Ccpe111 n2 internalNode111 0.0224537
* Tau 2973.95 s, freq 5.35163e-05 Hz
Rcpe112 n1 internalNode112 132142
Ccpe112 n2 internalNode112 0.0225058
* Tau 3278.93 s, freq 4.85386e-05 Hz
Rcpe113 n1 internalNode113 145356
Ccpe113 n2 internalNode113 0.022558
* Tau 3615.19 s, freq 4.4024e-05 Hz
Rcpe114 n1 internalNode114 159891
Ccpe114 n2 internalNode114 0.0226103
* Tau 3985.93 s, freq 3.99292e-05 Hz
Rcpe115 n1 internalNode115 175880
Ccpe115 n2 internalNode115 0.0226627
* Tau 4394.69 s, freq 3.62153e-05 Hz
Rcpe116 n1 internalNode116 193468
Ccpe116 n2 internalNode116 0.0227153
* Tau 4845.37 s, freq 3.28468e-05 Hz
Rcpe117 n1 internalNode117 212815
Ccpe117 n2 internalNode117 0.0227679
Rconvergence n1 n2 21281.532275247235
* Tau 0.0481172 s, freq 3.30765 Hz
Rcpe118 n1 internalNode118 2.77758
Ccpe118 n2 internalNode118 0.0173234
* Tau 0.0436417 s, freq 3.64685 Hz
Rcpe119 n1 internalNode119 2.52507
Ccpe119 n2 internalNode119 0.0172834
* Tau 0.0395825 s, freq 4.02084 Hz
Rcpe120 n1 internalNode120 2.29552
Ccpe120 n2 internalNode120 0.0172434
* Tau 0.0359009 s, freq 4.43318 Hz
Rcpe121 n1 internalNode121 2.08683
Ccpe121 n2 internalNode121 0.0172035
* Tau 0.0325616 s, freq 4.88781 Hz
Rcpe122 n1 internalNode122 1.89712
Ccpe122 n2 internalNode122 0.0171637
* Tau 0.029533 s, freq 5.38905 Hz
Rcpe123 n1 internalNode123 1.72466
Ccpe123 n2 internalNode123 0.017124
* Tau 0.0267861 s, freq 5.9417 Hz
Rcpe124 n1 internalNode124 1.56787
Ccpe124 n2 internalNode124 0.0170844
* Tau 0.0242947 s, freq 6.55103 Hz
Rcpe125 n1 internalNode125 1.42534
Ccpe125 n2 internalNode125 0.0170449
* Tau 0.022035 s, freq 7.22284 Hz
Rcpe126 n1 internalNode126 1.29576
Ccpe126 n2 internalNode126 0.0170054
* Tau 0.0199854 s, freq 7.96355 Hz
Rcpe127 n1 internalNode127 1.17796
Ccpe127 n2 internalNode127 0.0169661
* Tau 0.0181265 s, freq 8.78021 Hz
Rcpe128 n1 internalNode128 1.07088
Ccpe128 n2 internalNode128 0.0169268
* Tau 0.0164406 s, freq 9.68063 Hz
Rcpe129 n1 internalNode129 0.973524
Ccpe129 n2 internalNode129 0.0168877
Cconvergence n1 n2 7.283186964670183
.ends
******************************
.end
```

Appendix C: Solartron 1260A excerpt

C.1 Excerpt from Solartron 1260A manual, full version available at ***https://www.ameteksi.com***

5.1 GENERATOR

The generator drives the item under test (IUT). The drive signal parameters are shown in Figure 5.1.

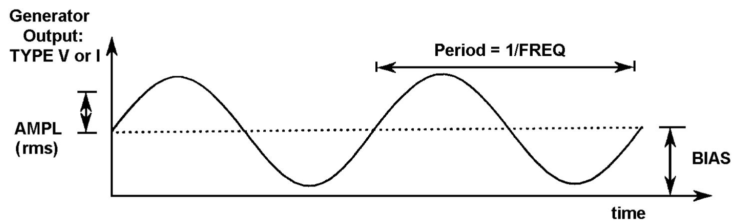


Figure 5.1 - Drive signal parameters

5.1.1 [GENERATOR]

Type of drive and constant voltage drive parameters.

TYPE Selects constant voltage or constant current drive:

- **[voltage]** Constant voltage drive:

  With MONITOR ENABLE set to [monitor off] the amplitude of the generator output voltage is held at the VAMPL value.

  With MONITOR ENABLE set to [monitor V1, target = V AMPL] the generator output is varied between 0V and V LIMIT in an attempt to hold the analyzer VOLTAGE 1 input at the V AMPL value.

  With MONITOR ENABLE set to [monitor 1, target = I AMPL] the generator output is varied between 0V and V LIMIT in an attempt to hold the analyzer CURRENT input at the I AMPL value.

- **[current]** Constant current drive:

  With MONITOR ENABLE set to [off] the amplitude of the generator output current is held at I AMPL value. (Set up the drive current parameters from the [GENERATOR Cont] page.)

  With MONITOR ENABLE set to [monitor V1, target = V AMPL] the generator output is varied between 0mA and I LIMIT in an attempt to hold the analyzer VOLTAGE 1 input at the V AMPL value.

  With MONITOR ENABLE set to [monitor I, target = I AMPL] the generator output is varied between 0mA and I LIMIT in an attempt to hold the analyzer CURRENT input at the I AMPL value.

FREQ Frequency of generator output. This is selectable in the range 10μHz to 32MHz. To vary the frequency progressively, use SWEEP.

V. AMPL Constant voltage ac amplitude, in the range 0V to 3V rms ($f \leq$ 10MHz) and 0V to 1V (f > MHz).

V. BIAS Constant voltage dc level, in the range -40.95V to =40.95V. Used for setting the quiescent operating point of the IUT or for nulling a dc offset.

5.1.2 [GENERATOR Cont]

Type of drive and constant current drive parameters.

TYPE Selects constant voltage or constant current drive. Duplicate of TYPE in Section 1.1 above.

FREQ Frequency of generator output. Duplicate of FREQ in Section 1.1 above.

I AMPL Constant current ac amplitude, in the range 0mA to 60mA rms ($f \leq$ 10MHz) and 0mA to 20mA rms (f > 10MHz).

I BIAS Constant voltage dc level, in the range -l00mA to + l00mA. Used for setting the quiescent operating point of the IUT or for nulling a dc offset.

5.1.3 [MONITOR]

Constant input signal parameters.

ENABLE Selects a constant signal level at the analyzer VOLTAGE 1 or CURRENT input. (In monitor mode the displayed amplitude variable represents the actual generator output.)

- **[monitor off]**
  Monitor facility off: generator output held at V AMPL or I AMPL value, in accordance with TYPE setting. (See Sections 1.1 and 1.2 above.)
- **[monitor V1, target = V. AMPL]**
  Constant voltage input. Generator output is adjusted automatically to hold the analyzer VOLTAGE 1 input at V AMPL ±ERROR%. During this process the generator output is not allowed to exceed the V LIMIT value.
- **[monitor I, target = I. AMPL]**
  Constant current input. Generator output is adjusted automatically to hold the analyzer CURRENT input at I AMPL ± ERROR%. During this process the generator output is not allowed to exceed the I LIMIT value.

V LIMIT Maximum amplitude voltage allowed at generator output in [monitor V1, target = V. AMPL] mode. (Default value = 3V.)

I LIMIT Maximum amplitude current allowed at generator output in [monitor I, target l. AMPL] mode. (Default value 60mA.)

ERROR% Percentage difference (1% to 50%) allowed between the generator output and the target value, in monitor mode.

A failure to obtain a target value within the defined error percentage (after two attempts) results in the error message "84. MONITOR FAILED".

5.1.4 MONITOR CONFIGURATIONS

To hold an input signal at a constant level the instrument uses one of the feedback configurations schematized in Fig 5.2. These configurations are part hardware and part software and, excluding the IUT, are contained in the instrument. In each case the generator output is varied, within defined limits, to maintain the selected input at a defined level. An amplitude sweep with monitor enabled sweeps the selected input.

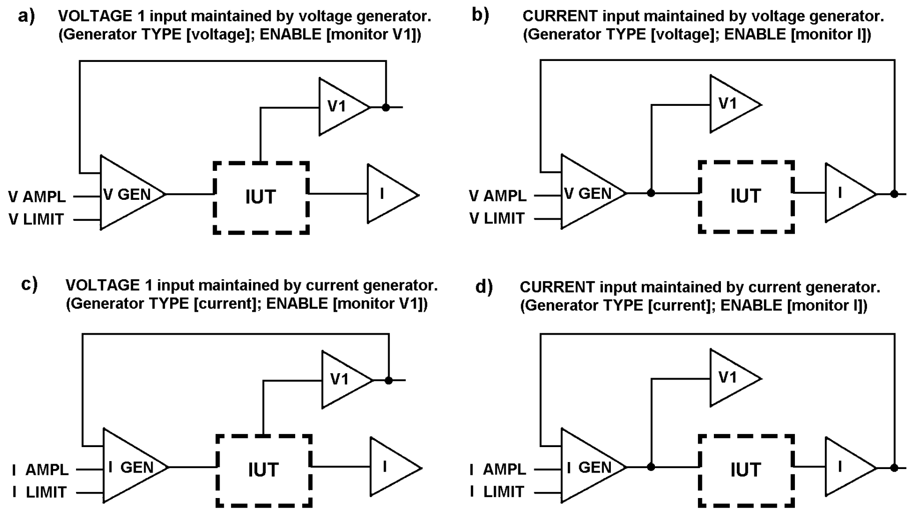


Figure 5.2 - Simplified schematic of monitor feedback configurations

5.1.5 GENERATOR START AND STOP CONTROL

The generator output is switched on, and stays on, when a measurement, SINGLE or RECYCLE, is commanded or when NULL [evaluate] or NORMALIZE [evaluate] is commanded.

BREAK switches the output off.

Other commands that switch the generator output off are:

KILL — This remotely generated signal is applied to a connector on the rear panel. When asserted, it holds the generator output at zero volts; when released, it allows the excitation signal to assume its set amplitude.

KILL also halts measurement data processing. Processing restarts, after KILL is released, with the next complete measurement.

Note that, with low frequency measurements, you may have to wait a considerable time for the measurement results to appear. For example, when measuring at 1mHz, the present (“killed”) measurement will take up to 1000 secs to complete. Then, assuming KILL was released during this period, you will have to wait another 1000 secs for the results of the “released” measurement.

SELF TEST — Same action on generator output as BREAK.

RESET — Sets the AMPL value in the GENERATOR menu to zero.

INITIALIZE — Same action on generator output as RESET.

Appendix D: Super-Capacitor datasheets

D.1 Datasheets for the various super-capacitors used in this research.

Panasonic **Electric Double Layer Capacitors (Gold Capacitor)**

Radial lead Type

Series : **HW**

Features

- Guaranteed at 70 °C (60°C 1000 h)
- Can be discharge mA or more current
- RoHS compliant

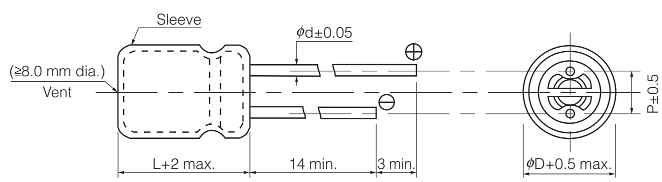
Recommended Applications

- Solar battery operated circuits (Road guidance flasher), Quick charging motor drives (Toy car)
- Back-up Power Supplies (UPS)

Specifications

Category temp. range	–25 °C to +70 °C		–25 °C to +60 °C	
Maximum operating voltage	2.3 V.DC		2.3 V.DC	2.1 V.DC
Nominal cap. range	22 F		30, 50 F	70 F
Characteristics at low Temperature	Capacitance change	±30 % of initial measured value at +20 °C (at –25 °C)		
	Internal resistance	≦4 times of initial measured value at +20 °C (at –25 °C)		
Endurance	After 1000 hours application of 2.3 V.DC at +70 °C (+60 °C), the capacitor shall meet the following limits.			
	Capacitance change	±30 % of initial measured value		
	Internal resistance	≦2 time of initial specified value		
Shelf Life	After 1000 hours storage at +70 °C (+60 °C) without load, the capacitor shall meet the specified limits for Endurance.			

Dimensions in mm(not to scale)



(Unit : mm)

Capacitance (F)	φD	L	φd	P
22	18.0	35.0	0.8	7.5
30	18.0	35.0	0.8	7.5
50	18.0	40.0	0.8	7.5
70	18.0	50.0	0.8	7.5

Characteristics list

✻ : 10 F or less HW series is not recommended for new design. Please consider HZ series.

Category temp. range (°C)	Maximum operating voltage (V.DC)	Capacitance (F)	Capacitance tolerance (F)	Internal resistance (Initial specified value) (Ω) at 1 kHz	Recommended discharge current (A)	Parts number	Mass (Reference value) (g)	Min. packaging q'ty (pcs)
–25 to +70	2.3	22	17.6 to 30.8	≦0.1	1 or less	EECHW0D226	12.0	50
–25 to +60		30	24.0 to 42.0	≦0.1	1 or less	EECHW0D306	14.0	50
		50	40.0 to 70.0	≦0.1	1 or less	EECHW0D506	15.0	50
	2.1	70	56.0 to 98.0	≦0.1	1 or less	EECHW0D706	19.0	50

Note : 1. Do not use reflow soldering. (IR, Atmosphere heating methods, etc.)
Please refer to the page of “Application guidelines”.

Guidelines and precautions regarding the technical information and use of our products described in this online catalog.

- If you want to use our products described in this online catalog for applications requiring special qualities or reliability, or for applications where the failure or malfunction of the products may directly jeopardize human life or potentially cause personal injury (e.g. aircraft and aerospace equipment, traffic and transportation equipment, combustion equipment, medical equipment, accident prevention, anti-crime equipment, and/or safety equipment), it is necessary to verify whether the specifications of our products fit to such applications. Please ensure that you will ask and check with our inquiry desk as to whether the specifications of our products fit to such applications use before you use our products.

- The quality and performance of our products as described in this online catalog only apply to our products when used in isolation. Therefore, please ensure you evaluate and verify our products under the specific circumstances in which our products are assembled in your own products and in which our products will actually be used.

- If you use our products in equipment that requires a high degree of reliability, regardless of the application, it is recommended that you set up protection circuits and redundancy circuits in order to ensure safety of your equipment.

- The products and product specifications described in this online catalog are subject to change for improvement without prior notice. Therefore, please be sure to request and confirm the latest product specifications which explain the specifications of our products in detail, before you finalize the design of your applications, purchase, or use our products.

- The technical information in this online catalog provides examples of our products' typical operations and application circuits. We do not guarantee the non-infringement of third party's intellectual property rights and we do not grant any license, right, or interest in our intellectual property.

- If any of our products, product specifications and/or technical information in this online catalog is to be exported or provided to non-residents, the laws and regulations of the exporting country, especially with regard to security and export control, shall be observed.

<Regarding the Certificate of Compliance with the EU RoHS Directive/REACH Regulations>

- The switchover date for compliance with the RoHS Directive/REACH Regulations varies depending on the part number or series of our products.

- When you use the inventory of our products for which it is unclear whether those products are compliant with the RoHS Directive/REACH Regulation, please select "Sales Inquiry" in the website inquiry form and contact us.

We do not take any responsibility for the use of our products outside the scope of the specifications, descriptions, guidelines and precautions described in this online catalog.

Notices

■ Applicable laws and regulations

・This product complies with the RoHS Directive (Restriction of the use of certain hazardous substances in electrical and electronic equipment (DIRECTIVE 2011/65/EU and (EU)2015/863)).

・No Ozone Depleting Chemicals(ODC's), controlled under the Montreal Protocol Agreement, are used in producing this product.
We do not use PBBs or PBDEs as brominated flame retardants.

・Export procedure which followed export related regulations, such as foreign exchange and a foreign trade method, on the occasion of export of this product.

・These products are not dangerous goods on the transportation as identified by UN(United Nations) numbers or UN classification.

■ Limited applications

・This capacitor is designed to be used for electronics circuits such as audio/visual equipment, home appliances, computers and other office equipment, optical equipment, measuring equipment.

・High reliability and safety are required [be / a possibility that incorrect operation of this product may do harm to a human life or property] more. When use is considered by the use, the delivery specifications which suited the use separately need to be exchanged.

■ Intellectual property rights and licenses

・The technical information in this specification provides examples of our products' typical operations and application circuits. We do not guarantee the non-infringement of third party's intellectual property rights and we do not grant any license, right, or interest in our intellectual property.

Items to be observed

■ For specification

・This specification guarantees the quality and performance of the product as individual components.
The durability differs depending on the environment and the conditions of usage.
Before use, check and evaluate their compatibility with actual conditions when installed in the products.
When safety requirements cannot be satisfied in your technical examination, inform us immediately.

・Do not use the products beyond the specifications described in this document.

■ Upon application to products where safety is regarded as important

Install the following systems for a failsafe design to ensure safety if these products are to be used in equipment where a defect in these products may cause the loss of human life or other signification damage, such as damage to vehicles (automobile, train, vessel), traffic lights, medical equipment, aerospace equipment, electric heating appliances, combustion/ gas equipment, rotating rotating equipment, and disaster/crime prevention equipment.

(1) The system is equipped with a protection circuit and protection device.
(2) The system is equipped with a redundant circuit or other system to prevent an unsafe status in the event of a single fault.

■ Conditions of use

・Before using the products, carefully check the effects on their quality and performance, and determined whether or not they can be used. These products are designed and manufactured for general-purpose and standard use in general electronic equipment. These products are not intended for use in the following special conditions.

(1) In liquid, such as Water, Oil, Chemicals, or Organic solvent.
(2) In direct sunlight, outdoors, or in dust.
(3) In vapor, such as dew condensation water of resistive element, or water leakage, salty air, or air with a high concentration corrosive gas, such as Cl_2, H_2S, NH_3, SO_2, or NOx.
(4) In an environment where strong static electricity or electromagnetic waves exist.
(5) Mounting or placing heat-generating components or inflammables, such as vinyl-coated wires, near these products.
(6) Sealing or coating of these products or a printed circuit board on which these products are mounted, with resin and other material.
(7) Using resolvent, water or water-soluble cleaner for flux cleaning agent after soldering. (In particular, when using water or a water-soluble cleaning agent, be careful not to leave water residues)
(8) Using in the atmosphere where strays acid or alkaline.
(9) Using in the atmosphere where there are excessive vibration and shock.

・Please arrange circuit design for preventing impulse or transitional voltage.
Do not apply voltage, which exceeds the full rated voltage when the capacitors receive impulse voltage, instantaneous high voltage, high pulse voltage etc.

・Our products there is a product are using an electrolyte solution. Therefore, misuse can result in rapid deterioration of characteristics and functions of each product. Electrolyte leakage damages printed circuit and affects performance, characteristics, and functions of customer system.

⚠ Application Guidelines (Gold Capacitor)

1. Circuit design

1.1 Product Life

The life of an electric double layer capacitor is limited. Its capacitance will decrease and its internal resistance will increase over time.
The life of a capacitor greatly depends on the ambient temperature, humidity, applied voltage and discharging currents. Capacitor life can be extended when these parameters are set well below the ratings.
The guaranteed durability of electric double-layer capacitors is between 1000 hours at 70 °C and 6000 hours at 85 °C. depending on product series. Generally, it is 1000 hours at 70 °C. The life of the capacitor is guaranteed to be 16000 hours at a normal temperature (30 °C) by applying the acceleration double for every 10 °C. Please choose the product that is suitable for the reliability that you need.
If your application incorporates this capacitor over a long period of time, then check it periodically and replace it when necessary.

1.2 Polarity and voltage

Capacitors have polarities.
Do not apply a reverse or AC voltage. If a reversed voltage is applied to a capacitor for a long period of time, then its life will be reduced and critical failures such as electrolyte leakage might occur.
Do not apply an over-voltage (a voltage exceeding the rated voltage).
If voltage exceeding the rating is applied to the capacitor for a long time, then its life will be reduced and critical failures such as electrolyte leakage or physical damage due to gas generated by electrochemical reaction or explosion might occur.

1.3 Circuits though which ripple currents pass

When using a capacitor in a circuit through which ripple currents pass, please note following matters.
(1) The internal resistance of electric double-layer capacitors is higher than that of electrolytic capacitors. Electric double-layer capacitors may generate heat due to ripple currents.
(2) Please do not exceed the maximum operating voltage when the voltage changes from ripple.
(3) Because internal resistance is high, the gold capacitor is not basically suitable for the absorption of ripple current.

1.4 Ambient temperature and product life

Capacitor life is affected by usage temperatures. Generally speaking, capacitor life is approximately doubled when the temperature is decreased by 10 °C. Therefore, lower the usage temperature as much as possible. Using capacitors beyond the guaranteed range might cause rapid deterioration of their characteristics and cause them to break down. The temperature referred to here includes the ambient temperature within the equipment, the heat produced by heat generating devices (power transistor, resistors, etc.), self-heating due to ripple currents, etc. Take all of these factors into consideration when checking the capacitor's temperature.
Do not place any heat generating devices on the back of the capacitors. Life acceleration can be calculated with the following equation :

$$L_2 = L_1 \times 2^{\left(\frac{T_1 - T_2}{10}\right)}$$

L_1 : Life at temperature T_1 °C (h)
L_2 : Life at temperature T_2 °C (h)
T_1 : Category s upper limit temperature
T_2 : Ambient temperature to calculate the life + heat generation due to ripple current (°C)

✻ Humidity also affects the capacitor's life. When using capacitors outside the following conditions, please contact us. A temperature at +55 °C and a relative humidity of 90 % to 95% for 500 hours.

Series	Max. Discharging Current				
	0.047 F or less	0.1 F to 0.33 F	0.47 F to 1.5 F	3.3 F to 4.7 F	10 F to 100 F
SG/SD/SE/NF/F	200 μA	300 μA	1 mA	—	—
RF (–40 °C, –25 °C)	—	300 μA, 3 mA	1 mA, 20 mA	—	—
LF (–40 °C)	—	—	1 mA	—	—
RG (–40 °C, –25 °C)	—	300 μA, 1 mA	1 mA, 20 mA	—	—

✻ The result that a very long term backup can be expected in calculation might be obtained by use conditions. However, please consider checking regularly and exchanging it when using it for the set that long-term reliability is basically demanded from the Gold Capacitor.

1.5 Voltage drop

Pay particular attention to the instantaneous working current and the voltage drop due to the capacitor's internal resistance when used in backup mode. The discharging current level is different depending on the capacitor's internal resistance. Use a capacitor with a discharging current below what is specified by the corresponding capacitor.

1.6 Series connection
When connecting capacitors in series, add a bleeder resistor in parallel with each capacitor by taking the leakage current into consideration so that the balance of voltages is not disrupted.
✻ Please present use condition about HZ/HW/HL series, and please contact us.

1.7 Electrolyte is used in the products
Electrolyte is used in the capacitors. Electrolyte leakage will damage printed circuit boards and can affect their performance, characteristics, and functions.

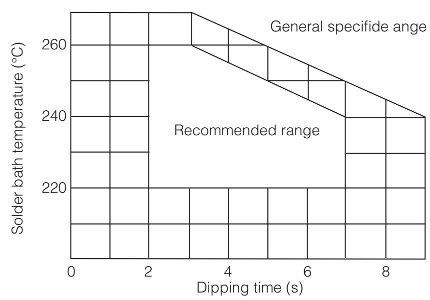
1.8 External sleeve
The external sleeve is not electrical insulation, and thus capacitors should not be used in an environment that requires electrical insulation. The sleeve is covered only for showing ratings.

2. Mounting

2.1 Heat stress at the soldering
When soldering a capacitor to a printed circuit board, excessive heat stress could cause the deterioration of the capacitor's electrical characteristics. For example the integrity of the seal can be compromised causing the electrolyte to leak, and short circuits could occur in addition to and failure of the appearance.
Please observe the following guidelines.

(1) Manual soldering
Do not touch the capacitor body with a soldering iron. Solder the capacitor using a soldering tip temperature of 350 °C or less for 4 seconds or less. Solder a the capacitor three times or less at intervals of 15 seconds or more.

(2) Flow soldering
1) Do not dip the body of the products into a soldering bath.
2) Keep the product's surface temperature at or below 100 °C for no more than 60 seconds (the peak 105 °C) when soldering. Please refer to the chart at right to set soldering temperature and time. It is recommended to check the product temperature before you use.
3) The terminals of the NF/F/RF/LF type are designed so the bottom of the product floats from the PWB. This is to protect against heat stress during soldering. Do not touch the bottom of the product directly to the PWB.



Pre-heating temperature : 110 °C or under(on the surface of circuit)
: 100 °C or under(on the surface of capacitor)
Pre-heating time : 60 seconds or under
Board thickness : 0.8 mm or more

(3) Other heat stress
1) Keep the product's surface temperature at or below 100 °C for no more than 60 seconds (the peak 105 °C) when applying heat to bake the PWB or fixing resin, etc.The capacitor voltage must be 0.3 V or less.
2) Do not use a product more than once after it has been mounted on the PWB. Excessive heat stress is applied when detaching it from the PWB. Please observe "(1) Manual soldering" when you adjusting it.
3) Be sure that excessive heat stress is not applied to the Gold capacitor when other parts in its surroundings of the Gold capacitor are detached or adjusted.

(4) Others
1) The lead wires and terminals are plated for solderability. Rasping or filing lead wires or terminals might damage the plating layer and degrade the solderability.
2) Do not apply a large mechanical force to the lead wires or terminals. Otherwise, they may break or come off or the capacitor characteristics may be damaged.
3) There is a possibility that the sealing performance of the product is deteriorated if a coating material that contains an organic solvent is used.

2.2 Circuit Design
Do not set wiring pattern directly under the mounted capacitor, and pass between terminals. If the electrolyte leaks, short circuit might occur and tracking or migrations are anticipated. If a capacitor is directly touching a PWB, then the bottom of the capacitorand the circuit pattern may short-circuit. On PWBs, blowing flux or solder may cause the capacitor's external sleeve to break or shrink, potentially affecting the internal structure. In addition, please refer to application guidelines for the aluminum electrolytic capacitor.

2.3 Residual voltage
Gold Capacitors can hold a large charge and could have residual voltage. Therefore, some electronic components with a low withstand voltage, such as semi-conductors, might be damaged.

2.4 Circuit board cleaning

Apply the following conditions for flux cleaning after soldering. (Excepted for NF/F/RF/LF series)
Please examine the SG/SD/RG series when washing is necessary.

Temperature : 60 °C or less
Duraiton : 5 minutes or less

Rinse sufficiently and dry the boards.
[Recommended cleaning solvents include]
Pine Alpha ST-100s, Sunelec B-12, DK be-clear CW-5790, Aqua Cleaner 210SEP, Cold Cleaner P3-375, Cllear-th-ru 750H, Clean-thru 750L, Clean-thru 710M, Techno Cleaner219, Techno Care FRW-17, Techno Care FRW-1, Techno Care FRV1

- Consult with us if you are using a solvent other than any of those listed above or Deionized water.
- The uses of ozone depleting cleaning agents is not recommended in the interest protecting the environment.

3. Precautions for using equipment

Avoid using mounting equipment in environments where :
(1) Capacitors are exposed to water, salt water or oil.
(2) Capacitors are exposed to direct sunlight.
(3) Capacitors are exposed to high temperature and humidity where water can condense on the capacitor surface.
(4) Capacitors are subject to various active gases.
(5) Capacitors are exposed to acidic or alkaline environments.
(6) Capacitors are subject to high-frequency induction.
(7)Capacitors are subject to excessive vibrations or mechanical impact.
A brown excretion might be caused around the sealing, depending on the conditions of use. This excretion is insulation and does not. have influence on the electrical characteristics.

4. Maintenance Precautions

Periodically check capacitors used in industrial equipment. When checking and maintaining capacitors, turn off the equipment and discharge the capacitors beforehand. Do not apply stress to the capacitor lead terminals.
Periodically check the following items.
1) Significant appearance abnormalities (deformation, electrolyte leakage, etc.)
2) Electrical characteristics (described in the catalog or delivery specifications)
If any abnormalities are found, then replace the capacitors or take appropriate actions.

5. Emergency procedures

If the capacitors generate heat, then smoke may come out of the exterior resin. Under these conditions turn off the equipment immediately and stop using it.
Do not place your face or hands close to the capacitor, burns might be caused.

6. Storage

Do not store capacitors in a high-temperature or high-humidity environment. Store capacitors at a room temperature of 5 to 35 °C and a relative humidity of 85 % or less. (Recommended storage term: 1year or less.)
Store capacitors in their packaging as long as possible. Avoid storing capacitors under the following conditions.
(1) Exposed to water, high temperatures or humidity, or when condensation can occurs.
(2) Exposed to oil or in environments filled with gaseous oil contents.
(3) Exposed to salt water or environments filled with saline substances.
(4) In environments filled with harmful gases
(hydrogen disulfide, sulfurous acid, nitrous acid, chlorine, bromine, bromomethane, etc.)
(5) In environments filled with harmful alkaline gases such as ammonia.
(6) Exposed to acid or alkaline solvents.
(7) Exposed to direct sunlight, ozone, ultraviolet or radial rays.
(8) Exposed to vibration or mechanical impact.

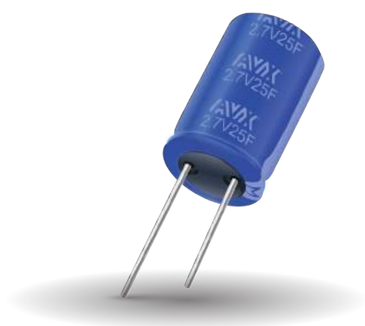
7. Discarding

Dispose of capacitors as industrial waste. They are comprised of various metals and resin.

The precautions for the use of Electric Double Layer Capacitors (Gold Capacitors) follow the “Precautionary guidelines for the use of fixed Electric Double Layer Capacitors for electronic equipment”, RCR-2370C issued by EIAJ in July 2008. Please refer to the above guidelines for details.

SCC Series SuperCapacitors

High Capacitance Cylindrical SuperCapacitors



The new series of cylindrical electrochemical double-layer capacitors offers excellent pulse power handling characteristics based on the combination of very high capacitance and very low ESR. Used by themselves or in conjunction with primary or secondary batteries, they provide extended back up time, longer battery life, and provide instantaneous power pulses as needed. Offers great solutions to Hold Up, Energy Harvesting, and Pulse Power Applications.

FEATURES

- Cap Values from 1F – 3000F
- High pulse power capability
- Low ESR
- Low Leakage Current

APPLICATIONS

- Camera Flash Systems
- Energy Harvesting
- GSM/GPRS Pulse Applications
- UPS/Industrial
- Wireless Alarms
- Remote Metering
- Scanners
- Toys and Games

HOW TO ORDER

SCC	R	12	B	105	P	R	B	_
Series SuperCap Cylindrical	**Diameter** Q = 6.3mm R = 8mm S = 10mm T = 12.5mm U = 16mm V = 18mm W = 22mm X = 30mm Y = 35mm Z = 60mm	**Case Length** Two digits represent case length in mm, with the exception of the following: 1A = 120mm 1E = 138mm 1F = 165mm	**Voltage Code** B = 2.7V	**Capacitance Code** 1st two digits represent significant figures 3rd digit represents multiplier (number of zeros to follow)	**Tolerance** P = +100%/-0% S = +30%/-10%	**Lead Format** R = Radial S = Solder Pin C = Cylindrical	**Package** B = Bulk T = Tray*	**Custom Code** A1= 4mm Bent Leads* C1 = 2mm Bent Leads*

*Inquire about availability

QUALITY INSPECTION

Parts are tested for Life Cycle, high temperature load life, temperature characteristics, vibration resistance, and humidity characteristics. See page 2 for more information.

TERMINATION

These SuperCapacitors are compatible with hand soldering, as well as reflow and wave soldering processes, so long as appropriate precautions are followed. See page 4 for more information.

OPERATING TEMPERATURE

-40°C to +65°C @ 2.7V
-40°C to +85°C @ 2.3V

LEAD-FREE
LEAD-FREE COMPATIBLE COMPONENT

RoHS COMPLIANT

For RoHS compliant products, please select correct termination style.

SCC Series SuperCapacitors

High Capacitance Cylindrical SuperCapacitors

RATINGS & PART NUMBER REFERENCE

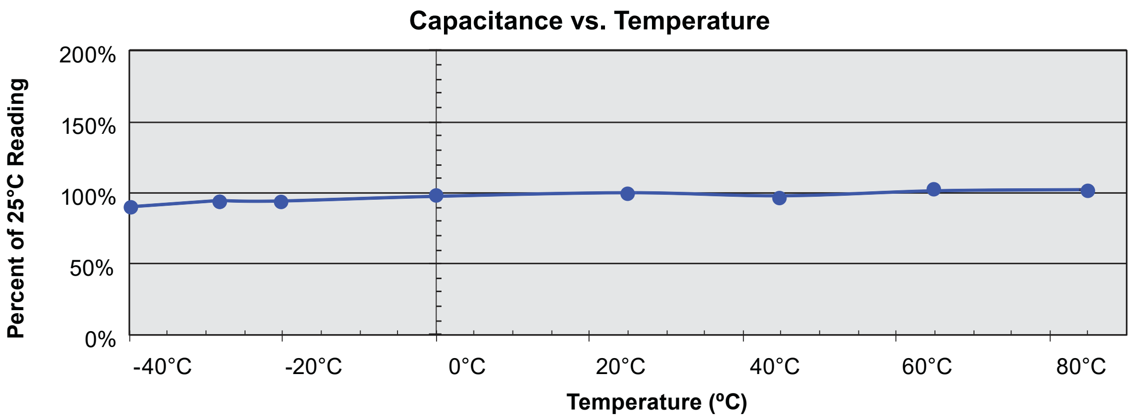
AVX Part Number	Diameter (mm)	Length (mm)	Rated Capacitance (F)	Capacitance Tolerance	Rated Voltage (V)	Rated Temperature (°C)	DCL Max @ 72 Hrs (µA)	ESR Max @ 1000 Hz (mΩ)	ESR Max @ DC (mΩ)	Peak Current (A)	Power Density (W/kg)	Max Energy (Wh)	Energy Density (Wh/kg)
Radial Lead													
SCCQ12B105PRB	6.3	12	1	+100%/-0%	2.7/2.3*	65/85*	6	200	500	0.90	2692	0.0010	1.56
SCCR12B105PRB	8	12	1	+100%/-0%	2.7/2.3*	65/85*	6	150	500	0.90	1842	0.0010	1.07
SCCR16B205PRB	8	16	2	+100%/-0%	2.7/2.3*	65/85*	10	100	360	1.57	2113	0.0020	1.76
SCCR20B335PRB	8	20	3.3	+100%/-0%	2.7/2.3*	65/85*	12	95	290	2.28	2080	0.0033	2.30
SCCS20B505PRB	10	20	5	+100%/-0%	2.7/2.3*	65/85*	15	70	180	3.55	2314	0.0051	2.41
SCCS25B705PRB	10	25	7	+100%/-0%	2.7/2.3*	65/85*	20	60	150	4.61	2243	0.0071	2.73
SCCS30B106PRB	10	30	10	+100%/-0%	2.7/2.3*	65/85*	30	40	75	7.71	3763	0.0101	3.27
SCCT20B106PRB	12.5	20	10	+100%/-0%	2.7/2.3*	65/85*	30	50	75	7.71	3431	0.0101	2.98
SCCT30B156SRB	12.5	30	15	+30%/-10%	2.7/2.3*	65/85*	50	35	80	9.20	2430	0.0152	3.38
SCCU25B256SRB	16	25	25	+30%/-10%	2.7/2.3*	65/85*	60	27	50	15.00	2397	0.0253	3.47
SCCU30B356SRB	16	30	35	+30%/-10%	2.7/2.3*	65/85*	70	20	40	19.69	2514	0.0354	4.07
SCCT47B406SRB	12.5	47	40	+30%/-10%	2.7/2.3*	65/85*	75	19	29	25.00	4022	0.0405	5.40
SCCV40B506SRB	18	40	50	+30%/-10%	2.7/2.3*	65/85*	75	18	20	33.75	3365	0.0506	3.89
SCCV60B107SRB	18	60	100	+30%/-10%	2.7/2.3*	65/85*	260	15	18	48.21	2430	0.1013	5.06
Solder Pin Lead													
SCCW45B107SSB	22	45	100	+30%/-10%	2.7/2.3*	65/85*	260	8	12	61.36	3391	0.1013	4.71
SCCX50B207SSB	30	50	200	+30%/-10%	2.7/2.3*	65/85*	600	6	9	96.43	2461	0.2025	5.13
SCCY62B307SSB	35	62	300	+30%/-10%	2.7/2.3*	65/85*	650	6	9	109.46	1262	0.3038	3.94
SCCY68B407SSB	35	68	400	+30%/-10%	2.7/2.3*	65/85*	1000	4	5	180.00	2046	0.4050	4.74
Cylindrical Lug Lead													
SCCZ1EB308SCB	60	138	3000	+30%/-10%	2.7/2.3*	65/85*	5200	0.2	0.29	2165.78	6033	3.0375	6.08

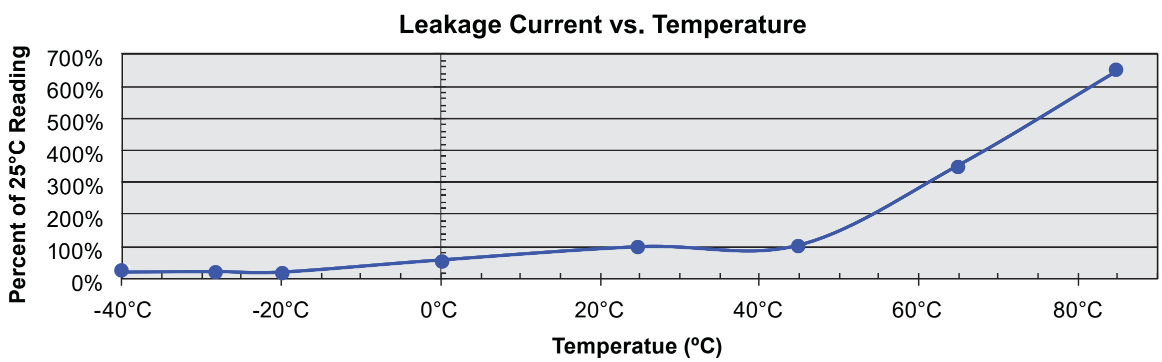
*with appropriate voltage derating operating temperature can be extended to 85°C

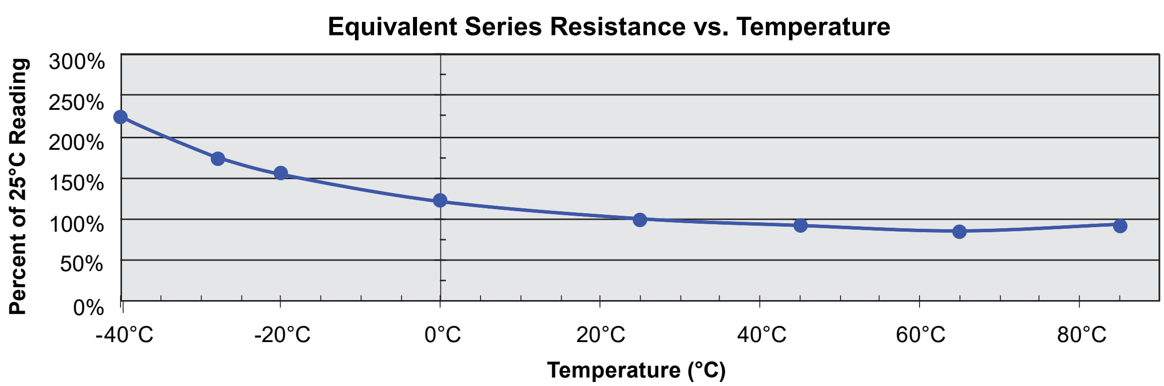
QUALIFICATION TEST SUMMARY

Test	Test Method	Parameter	Limits
Life Cycle	Capacitors are cycled between rated voltage and half-rated voltage under constant current at +25°C for 500,000 cycles	Capacitance Change ESR Appearance	≤30% of initial spec value ≤2 times initial spec value No remarkable defects
High Temperature Load Life	Temperature: +65°C Voltage: Rated Voltage Test Duration: 2,000 hours	Capacitance Change ESR Appearance	≤30% of initial spec value ≤2 times initial spec value No remarkable defects
Storage Temperature Characteristics	Storage Duration: 1 year No Load Temperature: +25°C	Capacitance Change ESR Appearance	≤30% of initial spec value ≤2 times initial spec value No remarkable defects
Vibration Resistance	Amplitude: 1.5mm Frequency: 10 ~ 55Hz Direction: X, Y, Z for 2 hours each	Capacitance Change ESR Appearance	≤30% of initial spec value ≤2 times initial spec value No remarkable defects
Humidity	Voltage: Rated Voltage RH: 90% Temperature: +60°C Test Duration: 1,500 hours	Capacitance Change ESR Appearance	≤30% of initial spec value ≤2 times initial spec value No remarkable defects

QUALITY AND RELIABILITY

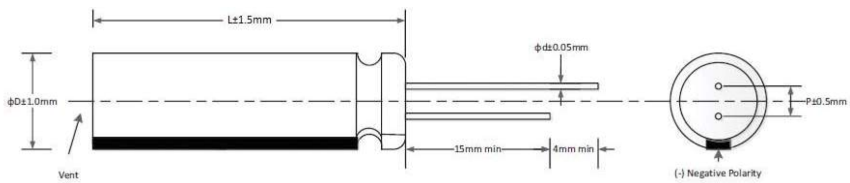






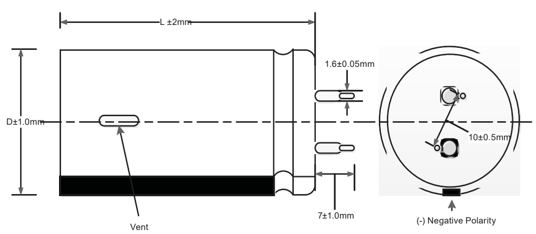
MECHANICAL SPECIFICATIONS

Radial Lead Type 1F – 100F

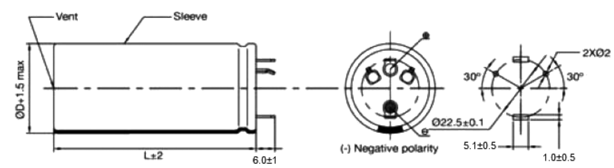


D (mm)	P (mm)	d (mm)
6.3	2.3	0.6
8	3.5	0.6
10	5.5	0.6
12.5	5.5	0.6
16	7.5	0.8
18	8	0.8

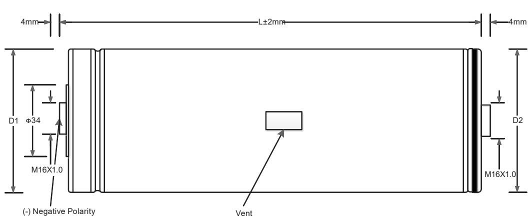
Solder Pin Type 2 pin 100F, 200F Part



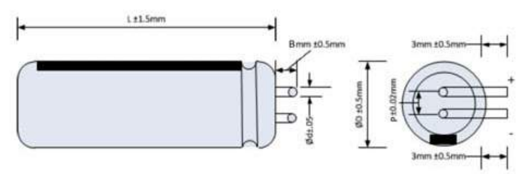
Solder Pin Type 4 pin 300F, 400F Part



Cylindrical Type 3000F Part



Radial Bent Lead Type



Style	B (mm)
A1	4
C1	2

SOLDERING RECOMMENDATIONS

When soldering SuperCapacitors to a PCB, the temperature & time that the body of the SuperCapacitor sees during soldering can have a negative effect on performance. We advise following these guidelines:

- Do not immerse the SuperCapacitors in solder. Only the leads should come in contact with the solder.
- Ensure that the body of the SuperCapacitor is never in contact with the molten solder, the PCB or other components during soldering.
- Excessive temperatures or excessive temperature cycling during soldering may cause the safety vent to burst or the case to shrink or crack, potentially damaging the PCB or other components, and significantly reduce the life of the capacitor.

HAND SOLDERING

Keep distance between the SuperCapacitor body and the tip of the soldering iron and the tip should never touch the body of the capacitor. Contact between SuperCapacitor body and soldering iron will cause extensive damage to the SuperCapacitor, and change its electrical properties. It is recommended that the soldering iron temperature should be less than 350°C, and contact time should be limited to less than 4 seconds. Too much exposure to terminal heat during soldering can cause heat to can cause heat to transfer to the body of the SuperCapacitor, potentially damaging the electrical properties of the SuperCapacitor.

WAVE SOLDERING

Only use wave soldering on Radial type SuperCapacitors. The PCB should be preheated only from the bottom and for less than 60 seconds, with temperature at, or below, 100°C on the top side of the board for PCBs equal to or greater than 0.8 mm thick.

Solder Temperature (ºC)	Suggested Solder Time (s)	Maximum Solder Time (s)
220	7	9
240	7	9
250	5	7
260	3	5

REFLOW SOLDERING

Infrared or conveyor over reflow techniques can be used on these SuperCapacitors. Do not use a traditional reflow oven without clear rated reflow temperature for SuperCapacitors.

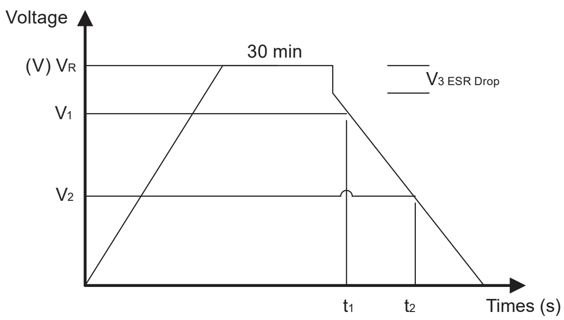
SCC Series SuperCapacitors

High Capacitance Cylindrical SuperCapacitors

TEST METHODS

IEC Capacitance Test Method

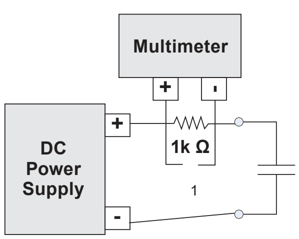
- Capacitance is measured using a Keithley 2400 or 2602 Meter
- Procedure
  - Charge Capacitor to Rated Voltage at room temperature
  - Disconnect parts from voltage to remove charging effects
  - Discharge cells with a constant current I determined by 4 * C * VR
  - Noting V1, t1, V2, t2 and performing the calculation for C



I – Discharge Current [mA], 4 * C * V_R V_R – Rated Voltage
V_1 – Initial Test Voltage, 80% of V_R
V_2 – Final Test Voltage, 40% of V_R
t_1 – Initial Test time
t_2 – Final Test time
$C = I * (t_2 – t_1) / (V_1 – V_2)$

DCL Measurement @ 25°C

- DCL is measured using a Multimeter with high internal impedance across a resistor
  - Charge Capacitor to Rated Voltage at room temperature for 72 Hours
  - Disconnect parts from Voltage by opening switch 1 (Stabilize for 10 Min)
  - Measure Voltage across a known Valued Resistor (1K Ohm)
  - Calculate DCL = V/R



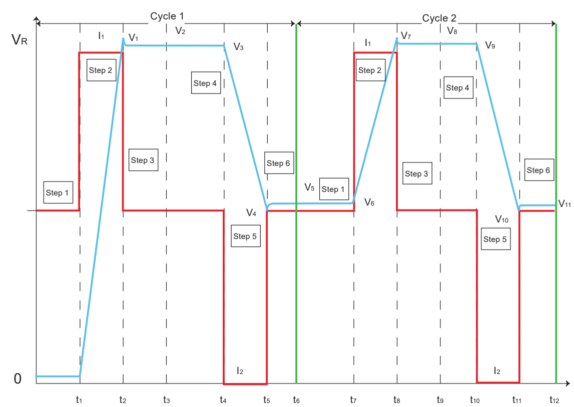
Initial ESR Measurement @ 25°C

- Using an Agilent 4263B LCR Meter and a Kelvin connection
  - Measure at frequency of 1000 Hz
  - Measurement Voltage of 10mV

DC ESR Measurement

- Six steps capacity and ESRDC Test Method is used as illustrated in the figure right.
- Tests are carried out by charging and discharging the capacitor for two cycles at rated voltage and half rated voltage
  - C = (CDC1+CDC2) / 2
  - ESRDC = (ESRDC1 + ESRDC2) / 2

  Where: CDC1 = I2*(t5-t4)/(V3-V4)
  CDC2 = I2*(t11-t10)/V9-V10)
  ESRDC1 = (V5-V4)/I2
  ESRDC2 = (V11-V10)/I2
  I1 = I2 = 75mA/F



Maximum Operating Current

- This is the maximum current when capacitor temperature rise of the capacitor during its operation is less than 15°C

Maximum Peak Current

- This is the maximum current in less than 1 sec

Watt Density

- Watt Density = $(0.12*V^2 / RDC)$ / mass

Energy Density

- Energy density = $(½ CV^2)$ / (3600*mass)

POLARITY / REVERSE VOLTAGE

In principal the positive and negative electrodes of the SuperCapacitors are symmetrical and in theory they should not have a polarity but for product consistency and for optimum performance the negative polarity is marked because the capacitors do not discharge completely when in use. It is recommended that the polarity should be used as marked. If the polarity is reversed the circuit will not have a catastrophic failure but the circuit will see a much higher leakage current for a short duration of time and the life time of the SuperCapacitors will be reduced.

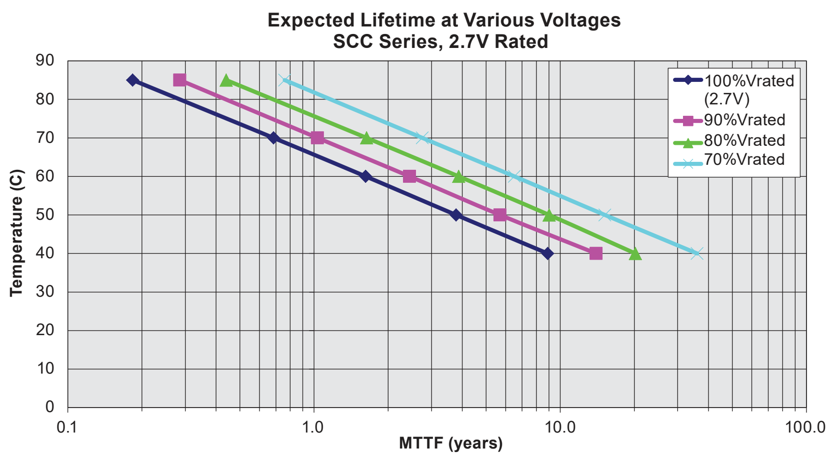
LIFE TIME AND TEMPERATURE PERFORMANCE

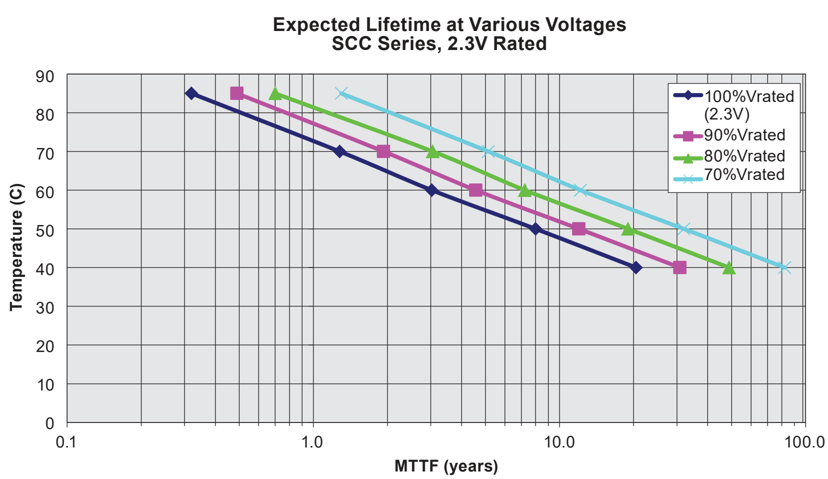
The life of a SuperCapacitor is impacted by a combination of operating voltage and the operating temperature according to the following equation:

time to failure, t ∞ Vn * exp (-Q / k*T) …………..(1)

where V is the voltage of operation, Q is the activation energy in electron volts (eV), k is the Boltzmann's constant in eV and T is the operating temperature in °K (where K is in degrees Kelvin). Typical values for the voltage exponent, n, is between 2.5 - 3.5, and Q is between 1.0 - 1.2 eV in the normal operating temperature range of 40° to 65°C.

The industry standard for SuperCapacitor end of life is when the equivalent series resistance, ESR, increases to 200% of the original value and the capacitance drops by 30%. Typically a super-capacitance shows an initial change in the ESR value and then levels off. If the capacitors are exposed to excessive temperatures the ESR will show a continuous degradation. In the extreme case, if the temperatures or voltages are substantially higher, than the rated voltage, this will lead to cell leakage or gas leakage and the product will show a faster change in the ESR which may increase to many times the original value.





SAFETY RECOMMENDATIONS

Warnings

- To Avoid Short Circuit, after usage or test, SuperCapacitor voltage needs to discharge to ≤ 0.1V
- Do not Apply Overvoltage, Reverse Charge, Burn or Heat Higher than 150°C, explosion-proof valve may break open
- Do not Press, Damage or disassemble the SuperCapacitor, housing could heat to high temperature causing Burns
- If you observe Overheating or Burning Smell from the capacitor disconnect Power immediately, and do not touch

Emergency Applications

- If Housing is Leaking:
  - Skin Contact: Use soap and water thoroughly to wash the area of the skin
  - Eye Contact: Flush with flowing water or saline, and immediately seek medical treatment
  - Ingestion: Immediately wash with water and seek medical treatment

Transportation

Not subjected to US DOT or IATA regulations
UN3499, <10Wh, Non-Hazardous Goods
International shipping description –
"Electronic Products – Capacitor"

Licenced by CAP-XX

Regulatory

- UL 810A
- RoHS Compliant
- Reach Compliant / Halogen Free

Storage

- Capacitors may be stored within the operating temperature range of the capacitor
- Lower storage temperature is preferred as it extends the shelf life of the capacitor
- Do Not Store the SuperCapacitors in the following Environments
  - High Temperature / High Humidity environments >70°C / 40% RH
  - Direct Sunlight
  - In direct contact with water, salt oil or other chemicals
  - In direct contact with corrosive materials, acids, alkalis, or toxic gases
  - Dusty environment
  - In environment with shock and vibration conditions

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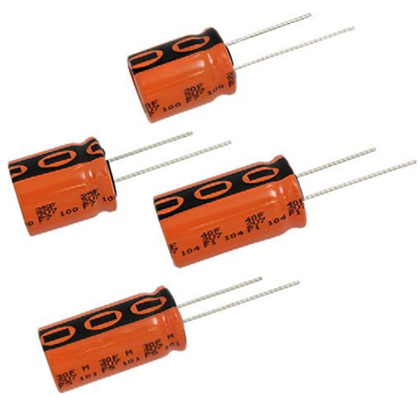
http://www.avx.com

AVX®

Ruggedized Electrical Double Layer Energy Storage Capacitors



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QUICK REFERENCE DATA	
DESCRIPTION	**VALUE**
Nominal case sizes (Ø D x L in mm)	16 x 20, 16 x 25, 16 x 31, 18 x 25, 18 x 20, **18 x 31**, 18 x 35, 18 x 40
Rated capacitance range, C_R	20 F to 60 F
Rated voltage, U_R (65 °C / 85 °C)	2.7 V / 2.3 V
Category temperature range	-40 °C to +85 °C
Biased humidity at 85 °C / 85 % RH	1500 h
Useful life at 85 °C	2000 h
Useful life at 20 °C	> 10 years
Shelf life at 20 °C	2 years
Cycle life	> 500 000 cycles

FEATURES

- Polarized energy storage capacitor with high capacity and energy density
- Rated voltage: 2.7 V
- Available in through-hole (radial) version
- Useful life: 2000 h at 85 °C
- Ruggedized for high humidity operation
- Rapid charge and discharge
- Maintenance-free, no service necessary
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

Pb-free
RoHS
COMPLIANT

APPLICATIONS

- Power backup
- Burst power support
- Storage device for energy harvesting
- Micro UPS power source
- Energy recovery

MARKING

The capacitors are marked (where possible) with the following information:

- Rated capacitance (in F)
- Rated voltage (in V)
- Date code, in accordance with IEC 60062
- Code indicating factory of origin
- Logo of manufacturer
- Negative terminal identification
- Series number (225)

PACKAGING

Supplied in ESD trays.

SELECTION CHART FOR C_R, U_R, AND RELEVANT NOMINAL CASE SIZES (Ø D x L in mm)	
C_R (F)	**U_R (V) = 2.7 V**
20	16 x 20
25	16 x 25; 18 x 20
30	18 x 25
35	16 x 31
40	**18 x 31** (1)
50	18 x 35
60	18 x 40

Note

(1) Preferred case size

DIMENSIONS in millimeters **AND AVAILABLE FORMS**

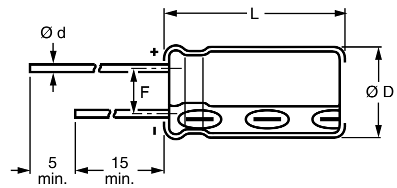

Fig. 1 - **Form CA:** Long leads

Table 1

DIMENSIONS in millimeters, **MASS, AND PACKAGING QUANTITIES**							
NOMINAL CASE SIZE Ø D x L	**CASE CODE**	**Ø d**	**Ø $D_{max.}$**	**$L_{max.}$**	**F**	**MASS (g)**	**PACKAGING QUANTITIES FORM CA IN TRAY**
16 x 20	19a	0.8	16.5	22	7.5 ± 0.5	≈ 6.0	200
16 x 25	19	0.8	16.5	27	7.5 ± 0.5	≈ 8.0	200
18 x 20	1820	0.8	18.5	22	7.5 ± 0.5	≈ 7.0	200
18 x 25	1825	0.8	18.5	27	7.5 ± 0.5	≈ 10.0	200
16 x 31	20	0.8	16.5	33.5	7.5 ± 0.5	≈ 9.0	200
18 x 31	1831	0.8	18.5	33.5	7.5 ± 0.5	≈ 12.5	200
18 x 35	22	0.8	18.5	37.5	7.5 ± 0.5	≈ 14.5	200
18 x 40	1840	0.8	18.5	42.5	7.5 ± 0.5	≈ 16.5	150

ELECTRICAL DATA	
SYMBOL	**DESCRIPTION**
C_R	Rated capacitance, tolerance -20 % / +50 %
I_P	Max. peak current
I_L	Max. leakage current after 0.5 h / 72 h at U_R

Note

- Unless otherwise specified, all electrical values in Table 2 apply at T_{amb} = 20 °C, P = 86 kPa to 106 kPa and RH = 45 % to 75 %

ORDERING EXAMPLE

Capacitor series 225 EDLC-R

40 F / 2.7 V

Nominal case size: Ø 18 mm x 31 mm; Form CA

Ordering code: MAL222591001E3

Table 2

ELECTRICAL DATA AND ORDERING INFORMATION															
U_R (V)	**U_{CT} (1) (V)**	**U_S (V) (< 1 s)**	**C_R (2) 100 Hz (F)**	**NOMINAL CASE SIZE Ø D x L (mm)**	**MAX. ESR_{DC} (2) INITIAL (mΩ)**	**MAX. ESR_{AC} INITIAL, 1 kHz (mΩ)**	**I_P MAX. PEAK CURRENT (A)**		**I_L MAX. LEAKAGE CURRENT AFTER (mA) (μA)**		**STORED ENERGY E AT U_R (Wh)**		**SPECIFIC ENERGY Ed AT U_R (Wh/kg)**		**ORDERING CODE MAL2225.......**
65 °C	**85 °C**						**65 °C**	**85 °C**	**0.5 h**	**72 h**	**65 °C**	**85 °C**	**65 °C**	**85 °C**	
2.7	2.3	2.85	20	16 x 20	24	18	25	20	8	75	0.020	0.015	3.4	2.3	91003E3
2.7	2.3	2.85	25	16 x 25	22	16	25	20	8	75	0.025	0.018	3.2	2.3	91006E3
2.7	2.3	2.85	25	18 x 20	20	15	25	20	8	75	0.025	0.018	3.6	2.6	91004E3
2.7	2.3	2.85	30	18 x 25	19	13	30	25	12	140	0.030	0.022	3.0	2.2	91007E3
2.7	2.3	2.85	35	16 x 31	20	14	30	25	15	200	0.035	0.026	3.8	2.9	91002E3
2.7	2.3	2.85	40	18 x 31	18	12	35	30	20	200	0.041	0.029	4.1	3.0	91001E3
2.7	2.3	2.85	50	18 x 35	15	10	35	30	25	250	0.051	0.037	3.5	2.6	91008E3
2.7	2.3	2.85	60	18 x 40	13	9	35	30	30	300	0.061	0.044	3.7	2.7	91009E3

Notes

(1) U_{CT} = rated voltage at upper category temperature

(2) Rated capacitance C_R and ESR_{DC}

Table 3

RUGGEDIZED FOR HIGH HUMIDITY - BIASED HUMIDITY TESTING		
PARAMETER	**PROCEDURE (AT RATED VOLTAGE)**	**REQUIREMENTS**
Humidity (relative)	85 %	After loading the capacitor for the specified time at maximum category temperature $T_{max.}$ = 85 °C and 85 % relative humidity, and related permissible maximum operating voltage U_R = 2.3 V, following parameters are valid within a timeframe of 1000 h: No visible damage No leakage of electrolyte ΔC/C: within ± 30 % of minimum initial specified value ESR: less than 3 x initial specified value Leakage: less than initial specified value
Temperature	85 °C	

TEST PROCEDURES AND REQUIREMENTS (1)		
NAME OF TEST	**PROCEDURE (quick reference)**	
Capacitance C_R and ESR_{DC}	Measured by DC discharging method as described in “Measuring of Characteristics”. (2)	
Maximum peak current	Non-repetitive current for maximum 1 s at specified operating temperature. Maximum operating voltage (refer to derating table) must not be exceeded. Usually to be tested with constant current discharge from U_R to 0.5 x U_R. Maximum current should not be used in normal operation and is only provided as reference value.	
Leakage current I_L	Measured at U_R. Capacitor is charged to the rated voltage at 20 °C. Leakage current is the current at specified time that is required to keep the capacitor charged at the rated voltage.	
Endurance	After loading the capacitor for specified time at maximum category temperature $T_{max.}$ = 85 °C and related permissible maximum operating voltage U_R = 2.3 V, following parameters are valid within a timeframe of 1000 h:	
	Capacitance	Within ± 30 % of minimum initial specified value
	ESR	Less than 3 x initial specified value
	Leakage	Within specified value
Useful life	After loading the capacitor for specified time at maximum category temperature $T_{max.}$ = 85 °C and related permissible maximum operating voltage U_R = 2.3 V, following parameters are valid within a timeframe of 2000 h:	
	Capacitance	Within ± 50 % of minimum initial specified value
	ESR	Less than 4 x initial specified value
	Leakage	Within specified value
Storage at upper category temperature	After loading the capacitor of specified time at maximum category temperature $T_{max.}$ = 85 °C and without charge and under 40 % RH, following parameters are valid within a timeframe of 1000 h:	
	Capacitance	Within ± 30 % of minimum initial specified value
	ESR	Less than 3 x initial specified value
	Leakage	Within specified value
Shelf life	Stored uncharged at 20 °C. Parameter within initial specification	
Cycle life	Cycles at 20 °C between rated voltage and half of rated voltage U_R with constant current 3 A and 1 s rest between charge and discharge: > 500 000 cycles	
	Capacitance	Within ± 30 % of minimum initial specified value
	ESR	Less than 3 x initial specified value
Stored energy E, specific energy Ed and Ev	E [Wh] = ½ x C x $(U_R)^2$ x 1/3600 Ed [Wh/kg] = ½ x C x $(U_R)^2$ x 1/3600 x 1/mass Ev [Wh/L] = ½ x C x $(U_R)^2$ x 1/3600 x 1/volume	
Soldering	Hand or wave soldering allowed. For details refer to soldering requirements for radial aluminum electrolytic capacitors in supplementary document.	
Cleaning	For printed circuit board cleaning apply non-aggressive cleaning agents only. For details refer to cleaning requirements for aluminum electrolytic capacitors in supplementary document.	
Environmental conditions	Do not expose capacitors to • temperatures outside specified range • high humidity atmospheres; except series 225 which is ruggedized for high humidity 85 °C and 85 % RH • corrosive atmospheres, e.g. halogenides, sulphurous or nitrous gases, acid or alkaline solutions, etc. • environments containing oil and grease	

Notes
- General remark: temperatures to be measured at capacitor case

(1) Conditions: electrical measurements at 20 °C, unless otherwise specified
(2) Rated capacitance C_R and ESR_{DC}

MEASURING OF CHARACTERISTICS

CAPACITANCE (C)

Capacitance shall be measured by constant current discharge method.

- Constant current charge with 10 mA/F to U_R
- Constant voltage charge at U_R for 5 min
- Constant current discharge with 10 mA/F to 0.1 V

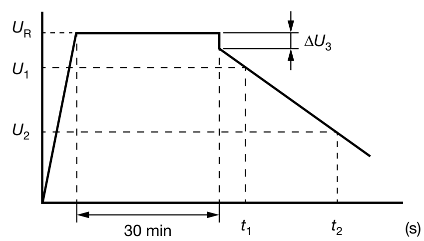

Fig. 2 - Voltage Diagram for Capacitance Measurement

Capacitance value C_R is given by discharge current I_D, time t and rated voltage U_R, according to the following equation:

$$C_R\ [F] = \frac{I_D\ [A] \times (t_2\ [s] - t_1\ [s])}{U_1\ [V] - U_2\ [V]}$$

C_R	Rated capacitance, in F
U_R	Rated voltage, in V
U_1	Starting voltage, 0.8 x U_R in V
U_2	Ending voltage, 0.4 x U_R in V
ΔU_3	Voltage drop at internal resistance, in V
t_1	Time from start of discharge until voltage U_1 is reached, in s
t_2	Time from start of discharge until voltage U_2 is reached, in s
I_D	Absolute value of discharge current, in A

EQUIVALENT SERIES RESISTANCE (ESR_{DC})

- Constant current charge to U_R
- Constant voltage charge at U_R for 5 min
- Constant current discharge to 0.1 V

$$ESR_{DC}\ [\Omega] = \frac{\Delta U_3\ [V]}{I_D\ [A]}$$

ESR_{DC}	Equivalent series resistance, in Ω
ΔU_R	Voltage drop at internal resistance, in V
I_D	Absolute value of discharge current, in A

Statements about product lifetime are based on calculations and internal testing. They should only be interpreted as estimations. Also due to external factors, the lifetime in the field application may deviate from the calculated lifetime. In general, nothing stated herein shall be construed as a guarantee of durability.

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XV Supercapacitor
Cylindrical snap-in

Description

Eaton supercapacitors are unique, ultra-high capacitance devices utilizing electrochemical double layer capacitor (EDLC) construction combined with new, high performance materials. This combination of advanced technologies allows Eaton to offer a wide variety of capacitor solutions tailored to specific applications that range from a few microamps for several days to several amps for milliseconds.

Features and benefits

- Over 10-year operating life at room temperature
- Ultra low ESR for high power density
- Large capacitance for high energy density
- Long cycle life
- UL Recognized

Applications

- Hybrid battery or fuel cell systems
- High pulse current applications
- UPS / hold up power

Powering Business Worldwide

Specifications

Capacitance	300 F to 600 F
Working voltage	2.7 V
Surge voltage	2.85 V
Capacitance tolerance	-5% to +10%
Operating temperature range	-40 °C to +65 °C
Extended operating temperature range	-40 °C to +85 °C (with voltage derating to 2.3 V @ +85 °C)

Standard Product[1]

Capacitance (F)	Part Number	Max. initial DC ESR (mΩ) (Equivalent Series Resistance)	Max continuous current[2] (A)	Peak current[3] (A)	Max leakage current[4] (mA)	Max power[5] (W)	Stored energy[6] (Wh)	Typical mass (g)
300	XV3550-2R7307-R	4.5	20	160	0.60	410	0.30	62
400	XV3560-2R7407-R	3.2	26	220	0.85	570	0.41	72
600	XV3585-2R7607-R	2.6	33	320	1.30	790	0.60	108

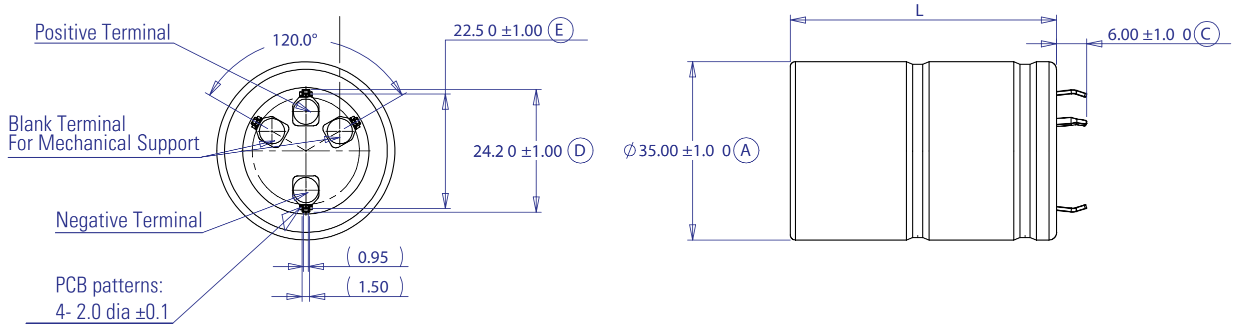
1. Capacitance, ESR and Leakage current are all measured according to IEC 62391-1 at +20 °C
2. 15 °C Temperature Rise
3. Peak Current is for 1 second = 1⁄2 Working Voltage x Capacitance / (1 + DC ESR x Capacitance)
4. Leakage current measured after 72 hours, +20 °C
5. Max. Power = Working Voltage^2 / 4 / DC ESR
6. Stored energy = 1⁄2 Capacitance x Working Voltage^2 / 3600

Performance

Parameter		Capacitance Change (% of initial value)	ESR (% of max. initial value)
Life			
@ Max. operating voltage and temp)	1500 hours	≤ 20%	≤ 200%
Charge/discharge cycling[1]	500,000	≤ 20%	≤ 200%
Storage Life- uncharged			
-40 °C to +65 °C	1500 hours	≤ 20%	≤ 200%
≤ 30 °C	3 years	≤ 5%	≤ 10%

1. Cycling between max operating and 50% of max operating voltage at room temperature

Dimensions (mm)



Part Number	L ±1.0
XV3550-2R7307-R	53
XV3560-2R7407-R	63
XV3585-2R7607-R	87.5

Part Numbering System

XV	3560		-	2R7	40	7	-R
Family Code	Size reference- mm Diameter	Length		Voltage (V) R = Decimal	Capacitance (µF) Value	Multiplier	
XV = Family Code	35	60		2R7= 2.7 V	Example: 407= 40 x 10^7µF or 400 F		Standard product

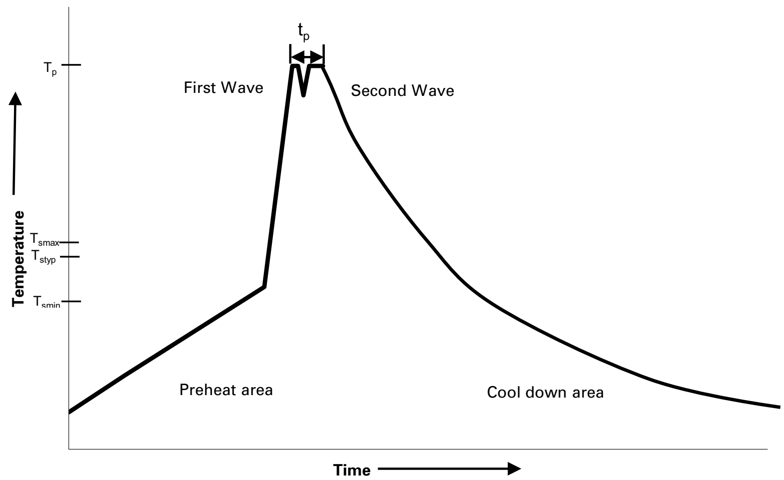
Packaging Information

- Standard packaging: 20 pieces per box

Part Marking

- Manufacturer
- Capacitance (F)
- Max operating voltage (V)
- Series code (or part number)
- Polarity

Wave solder profile



Profile Feature		Standard SnPb Solder	Lead (Pb) Free Solder
Preheat and soak	• Temperature max. (T_{smax})	100 °C	100 °C
	• Time max.	60 seconds	60 seconds
Δ preheat to max Temperature		160 °C max.	160 °C max.
Peak temperature (Tp)*		220 °C – 260 °C	250 °C – 260 °C
Time at peak temperature (t_p)		10 seconds max 5 seconds max each wave	10 seconds max 5 seconds max each wave
Ramp-down rate		~ 2 K/s min ~3.5 K/s typ ~5 K/s max	~ 2 K/s min ~3.5 K/s typ ~5 K/s max
Time 25 °C to 25 °C		4 minutes	4 minutes

Manual solder

+350 °C, 4-5 seconds. (by soldering iron), generally manual, hand soldering is not recommended.

Cleaning/Washing

Avoid cleaning of circuit boards, however if the circuit board must be cleaned use static or ultrasonic immersion in a standard circuit board cleaning fluid for no more than 5 minutes and a maximum temperature of +60 °C. Afterwards thoroughly rinse and dry the circuit boards. In general, treat supercapacitors in the same manner you would an aluminum electrolytic capacitor.

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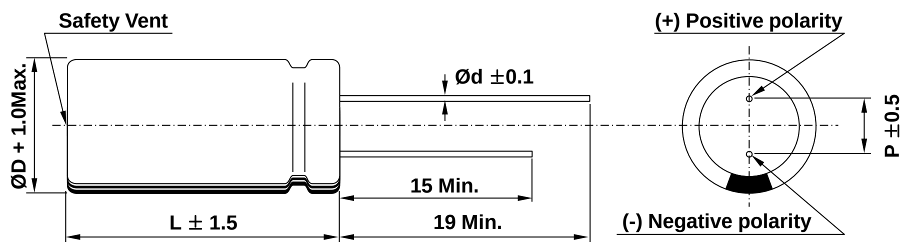
3.0V SERIES - Lead terminal

FEATURES

- High power density (Low ESR)
- Over 500,000 cycle life (semi-permanent)
- Higher energy density compared with 2.7V caps
- RoHS compliant

Drawing



D	8	10, 13	16, 18
d	0.6		0.8
P	3.5	5.0	7.5

SPECIFICATION

ITEM		CHARACTERISTICS	
Product series		EDLC	
Rated Voltage (V_R)		3.0V	
Operating Temperature		-40 ~ +65℃	
Capacitance Tolerance		-10 ~ +30%	
High Temperature Load Life		After 1,000 hours at V_R loaded under +65℃, capacitors meet the following criteria.	
		Capacitance Change	≤ 30% of initial value
		ESR	≤ 2 times of specified value
		85℃ Higher Temperature	Max. 2.4V
Cycle Life Characteristics	Cycle	Over 500,000	
	∆C	≤ 30% of initial value	
	ESR	≤ 2 times of specified value	
	Method	Cycle of Charge/discharge from V_R to $1/2V_R$	
Shelf Life		2 Years No Electrical Charge, Temperature below 70℃ (∆C : ≤ 10% of initial value / ∆ESR : ≤ 50% of specified value)	

3.0V SERIES - Lead terminal

Part Number	Rated Voltage (V)	Capacitance (F)	ESR (mΩ)		Max. Current (A)	Leakage Current (㎃, 72hr)	Size (㎜)	Weight (g)	Volume (mℓ)
			AC(1㎑)	DC			D × L		
VEC 3R0 105 QG	3.0	1	145	220	1.0	0.003	08 × 13	1.1	0.7
VEC 3R0 155 QG		1.5	95	140	1.5	0.005	08 x 20	1.4	1.0
VEC 3R0 335 QG		3.3	70	105	3.5	0.010	08 x 20	1.5	1.0
VEC 3R0 505 QD		5	40	70	5.5	0.015	08 x 25	1.8	1.3
VEC 3R0 505 QG		5	65	100	5.0	0.015	10 x 20	2.1	1.6
VEC 3R0 705 QG		7	65	110	5.5	0.021	10 x 20	2.2	1.6
VEC 3R0 106 QA		10	35	60	9.0	0.030	10 x 25	2.6	2.0
VEC 3R0 106 QG		10	25	40	10.0	0.030	10 x 30	3.2	2.4
VEC 3R0 156 QG		15	30	45	13.0	0.045	13 x 25	4.5	3.3
VEC 3R0 256 QG		25	20	30	21.0	0.075	16 x 25	7.2	5.0
VEC 3R0 506 QG		50	12.5	19	38.0	0.150	18 x 40	12.5	10.2
VEC 3R0 606 QG		60	12.5	19	42.0	0.180	18 x 40	13.5	10.2

*** Max. Current :** 1 sec. discharge to $1/2V_R$

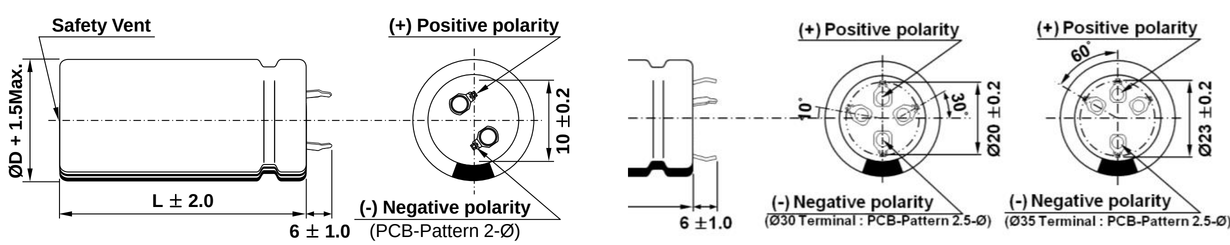
*** When do module more than 2 series, please fully discharge over 1 hour first, then assemble right after within 1 hour.**

3.0V SERIES – Snap-in terminal

FEATURES

- High power density (Low ESR)
- Over 500,000 cycle life (semi-permanent)
- Higher energy density compared with 2.7V caps
- RoHS compliant

Drawing



SPECIFICATION

ITEM		CHARACTERISTICS	
Product series		EDLC	
Rated Voltage (V_R)		3.0V	
Operating Temperature		-40 ~ +65℃	
Capacitance Tolerance		-10 ~ +30%	
High Temperature Load Life		After 1,000 hours at V_R loaded under +65℃, capacitors meet the following criteria.	
		Capacitance Change	≤ 30% of initial value
		ESR	≤ 2 times of specified value
		85℃ Higher Temperature	Max. 2.4V
Cycle Life Characteristics	Cycle	Over 500,000	
	ΔC	≤ 30% of initial value	
	ESR	≤ 2 times of specified value	
	Method	Cycle of Charge/discharge from V_R to $1/2V_R$	
Shelf Life		2 Years No Electrical Charge, Temperature below 70℃ (ΔC : ≤ 10% of initial value / ΔESR : ≤ 50% of specified value)	

3.0V SERIES – Snap-in terminal

Part Number	Rated Voltage (V)	Capacitance (F)	ESR (mΩ)		Max. Current (A)	Leakage Current (㎃, 72hr)	Size (㎜)	Weight (g)	Volume (mℓ)
			AC(1㎑)	DC			D × L		
VEC 3R0 107 QG	3.0	100	6.0	10.0	75.0	0.300	22×45	20.0	17.1
VEC 3R0 367 QG		360	3.0	4.5	200.0	1.080	35×62	70.0	59.6
VEC 3R0 407 QG		400	3.0	4.5	210.0	1.200	35×72	80.0	69.2
VEC 3R0 507 QG		500	3.0	4.5	230.0	1.500	35×82	96.0	78.9

*** Max. Current :** 1 sec. discharge to 1/2V_R

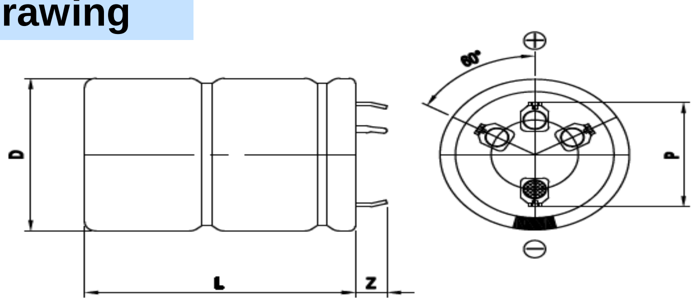
*** When do module more than 2 series, please fully discharge over 1 hour first, then assemble right after within 1 hour.**

3.0V 500F (3582)

Features

EDLC (Electric Double Layer Capacitor)
- High Power Density (Low ESR)
- Over 500,000 cycle life (semi-permanent)
- Higher energy density compared with 2.7V caps
- RoHS compliant

Drawing



D (Φ)	35 +1.5 Max
L (mm)	82 ±2.0
Z (mm)	6.0 ±1.0
P (mm)	23.0 ±0.2

Specification

Item		Characteristics	
Product series		EDLC	
Rated Voltage (V_R)		3.0V	
Operating Temperature		-40 ~ +65℃	
Capacitance Tolerance		-10 ~ +30%	
High Temperature Load Life		After 1,000 hours at V_R loaded under +65℃, capacitors meet the following criteria.	
		Capacitance Change	≤ 30% of initial value
		ESR	≤ 2 times of specified value
		85℃ Temperature	Max. 2.4V
Cycle Life Characteristics	Cycle	Over 500,000	
	△C	≤ 30% of initial value	
	ESR	≤ 2 times of specified value	
	Method	Cycle of Charge/discharge from V_R to 1/2V_R	
Shelf Life		2 Years No Electrical Charge, Temperature below 70℃ (△C : ≤ 10% of initial value / △ESR : ≤ 50% of specified value)	

Part Number	Rated Voltage (V)	Capacitance (F)	ESR (mΩ)		Max. Current (A)	Leakage Current (㎃, 72hr)	Size(mm)
			AC(1㎑)	DC			D x L
VEC 3R0 507 QG	3.0	500	3.0	4.5	230.0	1.500	35 x 82

*** Max. Current** : 1 sec. discharge to 1/2V_R

Version 9.2 2019.02.21.

DGH

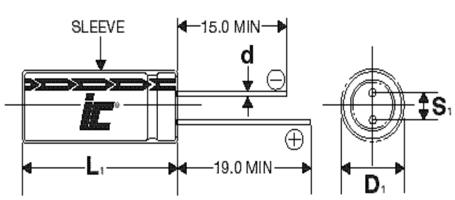
Low ESR Supercapacitor

FEATURES	Very Fast Charge/Discharge – High Power Density – Lower ESR – RoHS Compliant

APPLICATIONS	Battery Backup/Alternative – Pulse Power – Energy Harvesting – LED Displays – Mechanical Actuators – Audio Systems

Operating Temperature Range		**-40°C to +65°C** (-40 to +85°C @ 2.3V)		
Storage Temperature		-40°C to +70°C		
Capacitance Tolerance @ 20°C		+30%/-10% (Q tolerance)		
Voltage	**WVDC**	**2.7**	**5.5**	
	SVDC	**2.85**	**5.8**	
Life Time		**1000 hours with rated voltage applied at 65°C**		
		Capacitance change	≤30% of initially measured values	
		ESR	≤200% of initially specified values	
		Leakage current	≤100% specified maximum value	
Shelf Life		**1000 hours with no voltage applied at 60°C**		
		Capacitance change	≤30% of initially measured values	
		ESR	≤200% of initially specified values	
Life Cycles (25°C) 1 cycle= Charge to WVDC for 20s, constant voltage charging for 10s, discharge to ½ WVDC for 20s, rest for 10s		**500,000 cycles**		
		Capacitance change	<30% of initially measured values	
		ESR change	<200% of initially specified values	

D = 8 to 18mm



Lead spacing VS. Case diameter					
D	8	10	12.5	16	18
S	3.5	5.0	5.0	7.5	7.5
d	0.6	0.6	0.6	0.8	0.8
α	1.5	2.0	2.0	2.0	2.0

L_1=L+α mm
D_1=D+05mm
S_1=S±0.5mm

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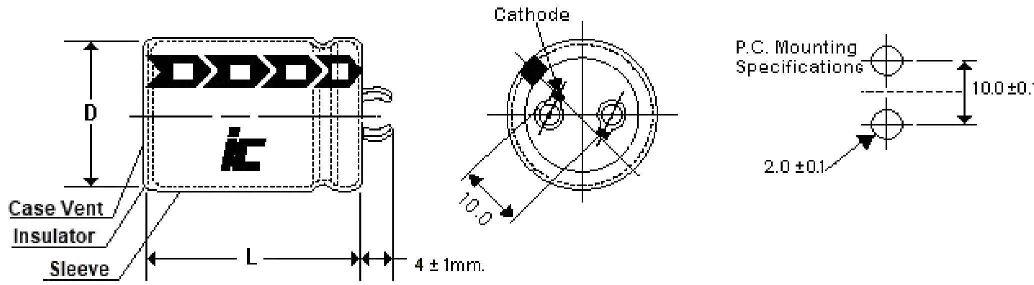
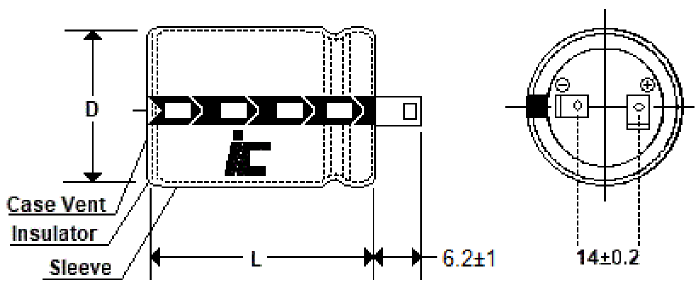
Low ESR Supercapacitor

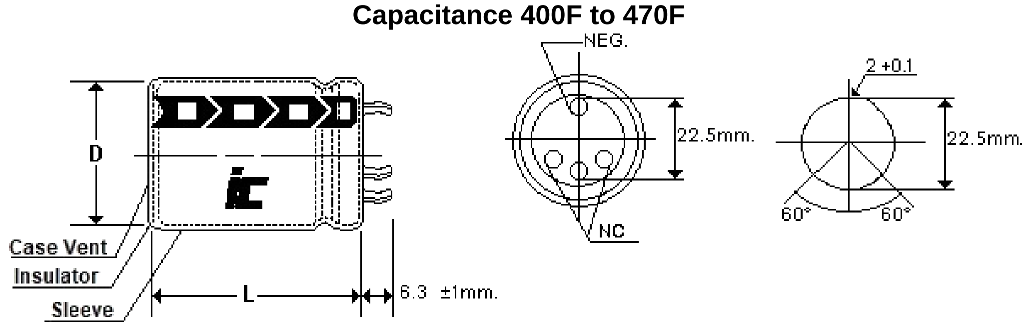
Capacitance 100F to 350F



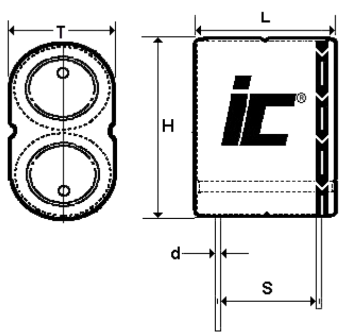


*Lead style L available for 350F

Capacitance 400F to 470F



5.5 Volt Parts



Capacitance (F)	Dims (LxHxT) (mm) +1.0mm	Lead spacing (S) (mm) +/-0.5mm	Lead diameter (d) (mm)
0.5	17x15x8.5	12	0.6
1	17x17x8.5	12	0.6
1.5	17x23x8.5	12	0.6
2.5	21x23x11	15.5	0.6
3.5	21x27x11	15.5	0.6
5	26x27x13	18	0.6

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High pulse power, extends battery life

Capacitance (F)	WVDC	IC PART NUMBER	MAX Current (A) (1 Sec.)	Maximum Continuous Current (A) (ΔT=15°C)	Short Circuit Current (A)	ESR AC 1 kHz (mΩ)	DC ESR (mΩ) 20°C	Max stored energy (mWh)	LC (mA), (72 hrs)	Energy Density (Wh/kg)	Energy Volumetric Density (Wh/l)	Power Density (kW/kg)	Power Volumetric Density (kW/l)
0.5	5.5	DGH504Q5R5	0.982	0.6	6.875	400	800	2.101	0.008	0.955	0.855	2.063	1.847
1.0	2.7	DGH105Q2R7	0.964	0.6	6.75	200	400	1.013	0.008	0.92	1.44	1.988	3.109
1.0	5.5	DGH105Q5R5	1.833	0.7	11	260	500	4.201	0.01	1.681	1.71	2.904	2.955
1.5	5.5	DGH155Q5R5	2.845	1.2	18.333	160	300	6.302	0.012	2.101	1.896	4.033	3.641
2.0	2.7	DGH205Q2R7	1.8	0.7	10.8	130	250	2.025	0.01	1.688	2.879	2.916	4.975
2.5	5.5	DGH255Q5R5	4.167	1.3	21.154	140	260	10.503	0.016	2.02	1.977	2.685	2.628
3.0	2.7	DGH305Q2R7	2.792	1.2	18	80	150	3.038	0.012	2.17	3.023	4.166	5.804
3.3	2.7	DGH335Q2R7	2.98	1.2	18	80	150	3.341	0.014	2.228	3.325	3.888	5.804
3.5	5.5	DGH355Q5R5	6.17	1.7	34.375	110	160	14.705	0.02	2.451	2.358	3.781	3.638
5.0	2.7	DGH505Q2R7	4.091	1.3	20.769	70	130	5.063	0.016	2.531	3.225	3.365	4.286
5.0	5.5	DGH505Q5R5	8.594	2.1	45.833	80	120	21.007	0.03	2.531	2.302	3.645	3.315
6.0	2.7	DGH605Q2R7	4.5	2.3	20.7	70	130	6.08	0.016	2.89	3.86	3.2	4.3
7.0	2.7	DGH705Q2R7	6.058	1.7	33.750	55	80	7.088	0.02	2.835	3.611	4.374	5.572
10.0	2.7	DGH106Q2R7	8.438	2.4	45	40	60	10.125	0.03	3.894	5.159	5.608	7.429
10.0	2.7	DGH106Q2R7B	8.438	2.1	45	40	60	10.125	0.03	2.978	4.299	4.288	6.191
10.0	2.7	DGH106Q2R7C	8.4	3.4	45.0	40	60	10.13	0.03	3.38	5.16	4.86	7.4
15.0	2.7	DGH156Q2R7	11.571	2.4	54	30	50	15.188	0.045	3.375	4.127	3.888	4.755
20.0	2.7	DGH206Q2R7	15	2.6	67.5	30	40	20.25	0.06	3.11	4.02	3.36	4.3
25.0	2.7	DGH256Q2R7	18	3.1	77.143	25	35	25.313	0.08	2.978	5.038	2.941	4.975
30.0	2.7	DGH306Q2R7	21.3	4.0	90	22	30	30.38	0.1	3.79	5.03	3.64	4.8
50.0	2.7	DGH506Q2R7	32.143	5.2	122.727	15	22	50.625	0.14	3.616	4.976	2.84	3.909
70.0	2.7	DGH706Q2R7	39.375	5.8	135	14	20	70.875	0.16	3.938	5.573	2.43	3.439
100.0	2.7	DGH107Q2R7	61.364	8.3	225	8	12	101.25	0.3	4.821	5.922	3.471	4.264
200.0	2.7	DGH207Q2R7	90	10	270	6	10	202.5	0.7	5.192	5.732	2.243	2.476
350.0	2.7	DGH357Q2R7	212.36	18.9	771.429	3	3.5	354.375	1	5.452	6.134	3.845	4.329
350.0	2.7	DGH357Q2R7L	212.36	18.9	771.4	3	3.5	354.4	1	5.452	6.134	3.845	4.329
400.0	2.7	DGH407Q2R7	236.84	18.9	843.750	2.8	3.2	405	1	5.956	7.016	4.02	4.736
470.0	2.7	DGH477Q2R7	239.89	18.9	771.429	3	3.5	475.875	1.3	6.609	8.244	3.471	4.33

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High pulse power, extends battery life

Capacitance (F)	WVDC	IC PART NUMBER	Weight (grams)	Volume (mL)	Dims DxL LxHxT (mm)	Lead Spacing S (mm)	Lead Diameter d (mm)
0.5	5.5	DGH504Q5R5	2.2	2.457	17x15x8.5	12	0.6
1.0	2.7	DGH105Q2R7	1.1	0.703	8x13	3.5	0.6
1.0	5.5	DGH105Q5R5	2.5	2.457	17x17x8.5	12	0.6
1.5	5.5	DGH155Q5R5	3	3.324	17x23x8.5	12	0.6
2.0	2.7	DGH205Q2R7	1.2	0.703	8x14	3.5	0.6
2.5	5.5	DGH255Q5R5	5.2	5.313	21x23x11	15.5	0.6
3.0	2.7	DGH305Q2R7	1.4	1.005	8x20	3.5	0.6
3.3	2.7	DGH335Q2R7	1.5	1.005	8x20	3.5	0.6
3.5	5.5	DGH355Q5R5	6	6.237	21x27x11	15.5	0.6
5.0	2.7	DGH505Q2R7	2	1.57	10x20	5	0.6
5.0	5.5	DGH505Q5R5	8.3	9.126	26x27x13	18	0.6
6.0	2.7	DGH605Q2R7	2.1	1.57	10x20	5	0.6
7.0	2.7	DGH705Q2R7	2.5	1.963	10x25	5	0.6
10.0	2.7	DGH106Q2R7	2.6	1.963	10x30	5	0.6
10.0	2.7	DGH106Q2R7B	3.4	2.355	12.5x25	5	0.6
10.0	2.7	DGH106Q2R7C	2.3	1.96	10x25	5	0.6
15.0	2.7	DGH156Q2R7	4.5	3.68	12.5x30	5	0.6
20.0	2.7	DGH206Q2R7	7	5.03	16x25	7.5	0.6
25.0	2.7	DGH256Q2R7	8.5	5.024	16x25	7.5	0.8
30.0	2.7	DGH306Q2R7	9.7	6.03	16x30	7.5	0.6
50.0	2.7	DGH506Q2R7	14	10.174	18x40	7.5	0.8
70.0	2.7	DGH706Q2R7	18	12.717	18x50	7.5	0.8
100.0	2.7	DGH107Q2R7	21	17.097	22x45	10	0
200.0	2.7	DGH207Q2R7	39	35.325	30x50	10	0
350.0	2.7	DGH357Q2R7	65	57.727	35x60	10	0
350.0	2.7	DGH357Q2R7L	65	57.727	35x60	18.4	0
400.0	2.7	DGH407Q2R7	68	57.727	35x60	22.5	0
470.0	2.7	DGH477Q2R7	72	57.727	35x60	22.5	0

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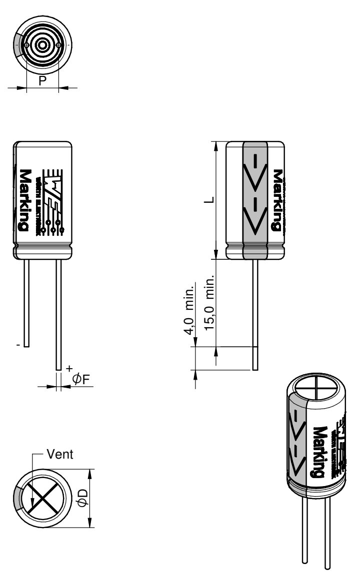
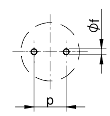
sales@illcap.com

Asia
Tel: 852 2793 0931
sales@illcap.com.hk

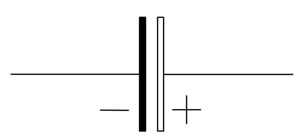
Dimensions: [mm]



Recommended Hole Pattern: [mm]



Schematic:



Electrical Properties:

Properties		Test conditions	Value	Unit	Tol.
Capacitance	C	10 mA/ F	7	F	+30%/-10%
Rated Voltage	U_R	@ 65 °C	2.7	V (DC)	max.
ESR	$R_{ESR\ DC}$	10 ms	45	mΩ	max.
ESR	$R_{ESR\ AC}$	5 mV @ 1 kHz	35	mΩ	max.
Rated Discharge Current	I_{Rated}		1.7	A	typ.
Max. Discharge Current	I_{Max}		7.1	A	typ.
Leakage Current	I_{Leak}	72 hrs. @ UR	0.02	mA	typ.
Power Density	P		18.92	kW/ kg	typ.
Energy Density	E		3.3	Wh/ kg	typ.

General Information:

Storage Conditions (in original packaging)	15 °C up to 35 °C; 10 % up to 75 % RH		
Operating Temperature	-40 up to +65 °C		
Life Cycle		500000	Cycles
Weight	m	2.1	g
Test conditions of Electrical Properties: +20 °C, 35 % RH if not specified differently			
Component conform to REACh and RoHS requirements and standards			

Dimensions:

Properties		Value	Unit	Tol.
Diameter	Ø D	10	mm	±1.5
Length	L	20	mm	±1.5
Pitch	P	5	mm	±0.5
Pin Diameter	Ø F	0.6	mm	±0.02
Pitch	p	5	mm	±0.5
Hole Diameter	Ø f	0.9	mm	±0.02

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WÜRTH ELEKTRONIK

CREATED	CHECKED	GENERAL TOLERANCE	PROJECTION METHOD
KaS	ReKa	DIN ISO 2768-1m	

DESCRIPTION	TECHNICAL REFERENCE
WCAP-STSC Supercapacitors (EDLC's)	STP1020705Q2R7DSPB95000
	ORDER CODE: **850617021002**

SIZE	REVISION	STATUS	DATE (YYYY-MM-DD)	BUSINESS UNIT	PAGE
10.0 x 20.0	001.000	Valid	2018-11-13	eiCap	1/9

Component Marking:

1st Line	Supercapacitor
2nd Line	EDLC Energy Capacity: 0.007 Wh
3rd Line	Rated Voltage: 2.7 V (DC) , Capacitance Value: 7 F , max. Temp. 65 °C
4th Line	Marking neg. Pol
5th Line	WCAP-STSC
6th Line	RU and Datecode YWW

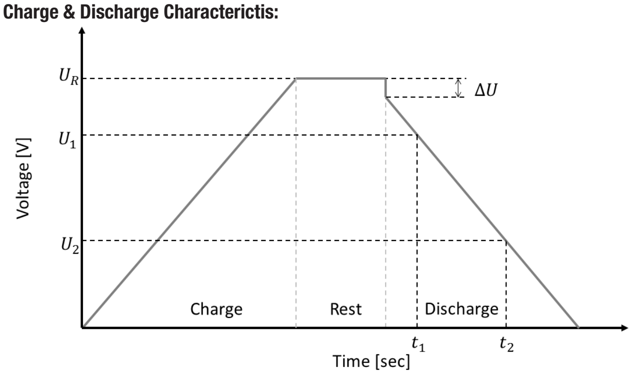
Life Time Performance:

Test Condition	Shelf Life	Cycle Life	Endurance
Life Time	up to 2 years	after 500000 cycles	1000 h, @65°C
Voltage	None	$U_{R\ applied}$	$U_{R\ applied}$
Current	None	I_R	I_R
Δ C	≤ 10% of initial value	≤ 30 % of initial measured value	≤ 30 % of initial measured value
Δ ESR	≤ 50% of specified value	≤ 2 x ESR	≤ 2 x ESR
Comments	25°C ± 10°C / 60% ±15% RH (dry and cool condition); discharged ≤ 0.2 V		

Additional Information:

Properties	Description	Formular
Max. Discharge Current I_{max} – [A]	is the current taking 1 sec. to discharge from U_R to $U_{R/2}$	$I_{max} = \frac{U_R/2}{1\,sec/C + R_s}$
Rated Discharge Current I_{Rated} – [A]	is the current taking 5 sec. to discharge from U_R to $U_{R/2}$	$I_{Rated} = \frac{U_R/2}{5\,sec/C + R_s}$
Leakage Current I_{Leak} – [mA]	is measured at 25°C (after holding 72 h at U_R)	
Power Density P – [kW/kg]	impedance matched with m (kg) as net weight for Capacitor	$P_{max} = \frac{U_R^2}{4 * R_s * m}$
Energy Density E – [Wh/kg]	with m(kg) as net weight for Capacitor	$E = \frac{C * U_R^2}{2 * 3600 * m}$
ESR R_{ESR} – [mΩ]	**$R_{ESR\ AC}$**: measured by contact resistance meter, conditions: Amplitude: 5 mV Frequency 1 kHz **$R_{ESR\ DC}$**: measured by constant current dicharge method (i.a.w. IEC62391) **I_{CC}**: constant discharge current	$R_{DC} = \frac{\Delta U}{I_{cc}}$
Capacitance C – [F]	I_{CC} [A]: constant discharge current U_1 [V]: U_R x 0.8 U_2 [V]: U_R x 0.4 t_1 [sec]: time at U_1 t_2 [sec]: time at U_2	$C = \frac{dQ}{dU} = I_{cc} * \frac{t_2 - t_1}{U_1 - U_2}$

Charge & Discharge Characterictis:

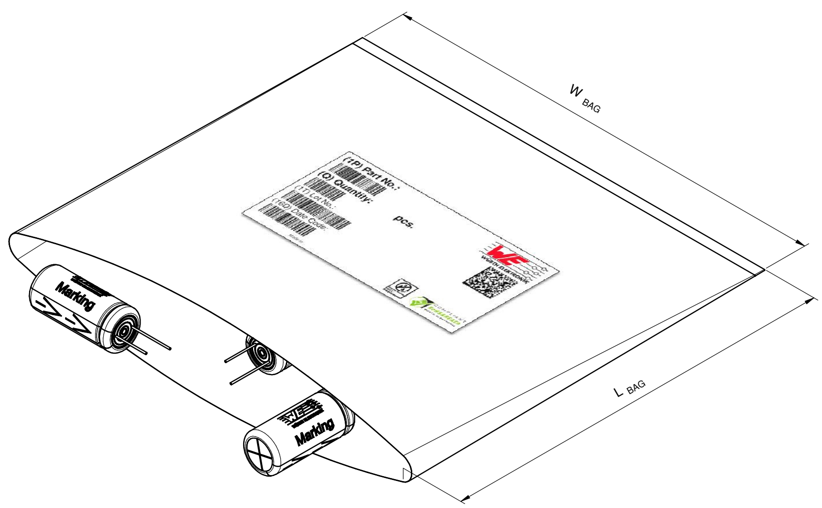


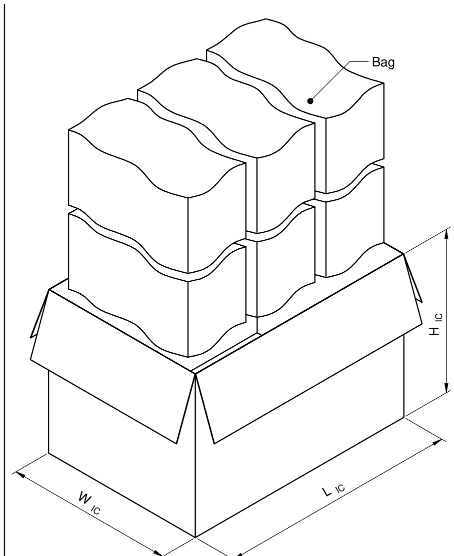
$U_1(t_1) = 0.8 \times U_R$

$U_2(t_2) = 0.4 \times U_R$

Würth Elektronik eiSos GmbH & Co. KG EMC & Inductive Solutions Max-Eyth-Str. 1 74638 Waldenburg Germany Tel. +49 (0) 79 42 945 - 0 www.we-online.com eiSos@we-online.com WÜRTH ELEKTRONIK	CREATED KaS	CHECKED ReKa	GENERAL TOLERANCE DIN ISO 2768-1m		PROJECTION METHOD	
	DESCRIPTION **WCAP-STSC Supercapacitors (EDLC's)**			TECHNICAL REFERENCE STP1020705Q2R7DSPB95000		
				ORDER CODE **850617021002**		
	SIZE 10.0 x 20.0	REVISION 001.000	STATUS Valid	DATE (YYYY-MM-DD) 2018-11-13	BUSINESS UNIT eiCap	PAGE 3/9

Packaging Specification - Bag and Carton: [mm]





L_{BAG} (mm)	W_{BAG} (mm)	Packaging Unit	Material
typ.	typ.	pcs.	
250,00	300,00	250	PE

L_{IC} (mm)	W_{IC} (mm)	H_{IC} (mm)	Packaging Unit	Material
typ.	typ.	typ.	pcs.	
287,00	202,00	195,00	1500	Paper

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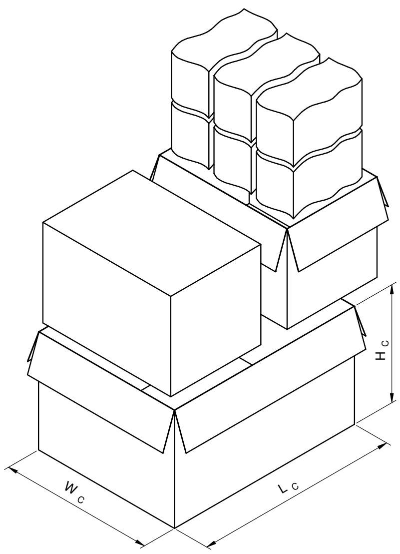
CREATED	CHECKED	GENERAL TOLERANCE	PROJECTION METHOD
KaS	ReKa	DIN ISO 2768-1m	

DESCRIPTION	TECHNICAL REFERENCE
WCAP-STSC Supercapacitors (EDLC's)	STP1020705Q2R7DSPB95000
	ORDER CODE: **850617021002**

SIZE	REVISION	STATUS	DATE (YYYY-MM-DD)	BUSINESS UNIT	PAGE
10.0 x 20.0	001.000	Valid	2018-11-13	eiCap	4/9



L_C (mm)	W_C (mm)	H_C (mm)	No. of inner Carton	Packaging Unit	Material
typ.	typ.	typ.	pcs.	pcs.	
404,00	305,00	229,00	2	3000	Paper

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CREATED	CHECKED	GENERAL TOLERANCE	PROJECTION METHOD
KaS	ReKa	DIN ISO 2768-1m	

DESCRIPTION
WCAP-STSC Supercapacitors (EDLC's)

TECHNICAL REFERENCE
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SIZE	REVISION	STATUS	DATE (YYYY-MM-DD)	BUSINESS UNIT	PAGE
10.0 x 20.0	001.000	Valid	2018-11-13	eiCap	5/9

The following conditions apply to all goods within the product series of Super Capacitors of Würth Elektronik eiSos GmbH & Co. KG:

General:

- This electronic component was designed and manufactured for use in general electronic equipment.
- Würth Elektronik must be asked for a written approval (following the certain PPAP level procedure) before incorporating the components into any equipment in the field such as military, aerospace, aviation, nuclear control, submarine, transportation (automotive control, train control, ship control), transportation signal, disaster prevention, medical, public information network etc. where higher safety and reliability are especially required and/or if there is the possibility of direct damage or human injury.
- Electronic components that will be used in safety-critical or high-reliability applications, should be pre-evaluated by the customer.
- Direct mechanical impact to the product shall be prevented as material of the body, pins or termination could flake or in the worst case it could break.
- Avoid any water or heavy dust on capacitors surface, which may cause electrical leakage, damage, overheating or corrosion.
- Würth Elektronik products are qualified according to international standards, which are listed in each product reliability report. Würth Elektronik does not guarantee any customer qualified product characteristic, beyond Würth Elektronik specifications, for its validity and sustainability over time.
- The customer is responsible for the functionality of their own products. All technical specifications for standard products also apply to customer specific products.
- The component was designed and manufactured to be used within the datasheet specified values. If the usage and operation conditions specified in the datasheet are not met, the body, pins or termination may be damaged or dissolved.
- Do not apply any kind of flexural or compressive force onto soldered or unsoldered component.
- The capacitance tolerance as specified within the datasheet is only valid on the date of delivery and according specified measurement criteria.

Product specific:

Polarity:

The product has a polarity. In operation this polarity needs to be considered and adhered. Reverse voltage can damage or destroy the product. The polarity is marked with a stripe and the word NEG as well as a negative sign on the lateral surface of the capacitor.

Overvoltage:

Avoid any overvoltage and do not apply a continuous overvoltage. If an overvoltage is applied to the capacitor, the leakage current can increase drastically. The applied working voltage is not allowed to exceed the rated working voltage of the specific capacitor.

Operating Temperature:

The capacitor shall not be operated above the operating temperature, which is stated within this datasheet of the specific capacitor. The achievable lifetime of the capacitor is correlating to the applied temperature. In order to achieve the maximum lifetime, the capacitor should be operated by the lowest possible temperature conditions within the application. During charging and discharging in a short cycles, self-heating is generated by internal resistance. The operating temperature should not exceed the above stated operating temperature, including any self-heating.

Charge and Discharge:

Frequent and quick charge / discharge cycles may generate heat inside the capacitor. Do not exceed the above stated discharge current. Exceeding the maximal current, stated above, can cause a decrease of capacitance, an increase of leakage current or breakdown. For assistance with your application please consult our technical support.

Storage Conditions:

The storage conditions for a capacitor are recommended to be as given above. Do not expose the capacitor to environments with hazardous gas, ozone, ultraviolet rays or any kind of radiation. Avoid any contact of the capacitor with direct sunshine, saltwater, spray of water or types of oil during storage. All products shall be used before the end of the period of 24 months based on the product date code, if not a 100 % solderability cannot be guaranteed. The capacitance tolerance as specified within the datasheet is only valid on the date of delivery.

Soldering:

The solder profile must comply with the Würth Elektronik technical soldering specification. All other profiles will void the warranty.All other soldering methods are at the customers' own risk.Strong forces which may affect the coplanarity of the components' electrical connection with the PCB (i.e. pins), can damage the part, resulting in avoid of the warranty.Do not use excessive nor insufficient flux.Provide enough washing when water-soluble flux is used.During wave soldering only the pins / terminals should have contact with hot solder bath / wave. Assure that no direct contact of capacitor body with hot solder bath / wave or any other component will happen. Soldering must be done from the opposite PCB side where capacitor body is placed.

Dangerous Goods and Handling:

Due to the European agreement concerning the international carriage of dangerous good by road (ADR) capacitors with an energy storage capacity of 0.3 Wh or more are considered as dangerous goods. Refer to special provision 361 for detailed information. Each capacitor should be protected against unintended short circuit or be fitted with a metal strap connecting the terminals, if transported. Capacitors installed in equipment shall be either in an uncharged state or protected against short circuit. A fully charged capacitor shall not be short circuited without a protective resistor of at least 1 kΩ.

Cleaning:

Do not wash the assembled capacitors with the following cleaning agents:

- Petroleum system solvents: may cause degeneration of the rubber seal material
- Alkali system solvents: may cause corrosion and dissolve of the casing
- Halogenated solvents: may cause corrosion and failure of the capacitor
- Acetone: component marking may be erased
- Aromatic solvents like xylene: may cause deterioration of the rubber seal material
- Verify the following points when washing is are applied to capacitors:
- Please monitor conductivity, ph-value, specific gravity and the water content of cleaning agents. Contamination adversely affects these characteristics.
- Be sure to not expose the capacitors under solvent rich conditions or keep capacitors inside a closed container. In addition, please dry the solvents on the PCB and the capacitor sufficiently with an air knife (temperature should be less than the maximum rated category temperature of the capacitor) for 10 minutes.
- Capacitors can be characteristically and catastrophically damaged by halogen ions, particularly by chlorine ions. The degree of the damage mainly depends upon the characteristics of the electrolyte and rubber seal material. When halogen ions come into contact with the inside of the capacitors, the foil may corrode, when a voltage is applied. This corrosion causes an extremely high leakage current, which results in venting and an open circuit defect.

All other cleaning processes and cleaning agents are not approved by Würth Elektronik eiSos. All cleaning methods need to be tested and validated by the customer.

Adhesives and Coating Materials:

The usage of any adhesive or coating material, which is containing halogenated solvents, is not allowed.Before applying adhesives or coating materials, make sure that the following points are fulfilled:

- Take care that the surface and capacitor is dry and clean before applying adhesive or coating, to avoid any contamination with flux residues or cleaning solvents.
- Assure that no flux residue or spot is left between the rubber seal material of the capacitor and the PCB.
- Do not fully cover the entire rubber seal surface with adhesive, coating or molding materials. Otherwise the covering of the full rubber seal surface may restrain the natural diffusion of hydrogen gas. Block maximum 80% of the sealed section of a capacitor.
- If the used adhesive, coating or molding material is containing halogen ions in a large amount, the halogen ions can diffuse and creep into the capacitor and can damage the capacitor. Both above explained circumstances can result in serious failures.
- Follow the specified heating and curing instructions given by supplier of the used adhesive or coating material. Avoid excessive pressure or heat on the capacitor by applying coating or adhesive.
- Take care that hardening of adhesive, coating material was correctly done, so that no solvents do remain.
- Be aware, that used solvents within adhesive and coating materials can damage the sleeve of the capacitor and can result in changes of the appearance of the sleeve (color, shine and marking).

Mechanical Stress on lead wire and terminal:

Do not stress the capacitor with the following actions:

- Applying any excessive force to the lead wire or terminal.
- Move or turn the capacitor after soldering to the PCB.
- Bending pins after soldering.
- Carrying the PCB by picking / holding the board via a capacitor.

Operation and Usage of the Capacitor:

In operation and usage take care about the following points.Do not use the capacitor within the following environmental conditions:

- Environment with high mechanical stress / shocks or vibration (please see this specific datasheet for permitted limits).
- Environment with high amount of damp condensation, water or types of oil.
- Direct sunlight, ozone, any kind of radiation or ultraviolet rays.
- Toxic gases (e.g. ammonium, chlorine and compounds, bromine and compounds, hydrogen sulfide, sulfuric acid).

User should never touch the terminals of the capacitor directly.Avoid short circuit between terminals with any kind of conductive material (e. g. metal, fluid, acid, alkaline solution).

Maintenance:

For industrial applications it is recommended to perform periodic inspections. Power supplies shall be turned off before inspection to discharge the capacitor. Check the following points in case of an inspection:

- Visual inspection of the capacitor to see, if the vent operated for pressure relief and if any leakage of electrolyte has taken place.
- Measurement of electrical characteristics of the capacitor (according to datasheet, especially leakage current, capacitance and ESR).

In case of deviation or failure according to the specified characteristics, take care to start appropriate actions (e.g. replacement of capacitor).

Emergency Case:

In case of excessive pressure within the capacitor the vent may operate and release this pressure. In case of vent operation gas becomes visible, when the component is in operation. If so, directly turn off the application and disconnect it from the power source. If the application will not be turned off, a possible short circuit of capacitor or a short circuit due to bridging of liquefied gas can possibly damage the circuit and in worst case the application may be dramatically damaged.Do not stay or position body or face above or in direction of the vent, because in the event of any vent operation, the releasing gas temperature may have over 100 °C.In case of contact with the electrolyte on skin, wash the skin immediately with soap and water. If the eyes will get in contact with the releasing gas, immediately wash the eyes with water. Whether the gas was inhaled, directly use gargle.

Disposal:

This capacitor shall be disposed of as industrial waste in accordance with local laws and regulations. Discharge capacitor before disposal. Never throw this device into fire. To avoid any explosion of capacitor, punch holes into the can or crush the capacitor before industrial waste incineration.

These cautions and warnings comply with the state of the scientific and technical knowledge and are believed to be accurate and reliable.
However, no responsibility is assumed for inaccuracies or incompleteness.

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CREATED	CHECKED	GENERAL TOLERANCE	PROJECTION METHOD
KaS	ReKa	DIN ISO 2768-1m	

DESCRIPTION	TECHNICAL REFERENCE
WCAP-STSC Supercapacitors (EDLC's)	STP1020705Q2R7DSPB95000
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Important Notes

The following conditions apply to all goods within the product range of Würth Elektronik eiSos GmbH & Co. KG:

1. General Customer Responsibility

Some goods within the product range of Würth Elektronik eiSos GmbH & Co. KG contain statements regarding general suitability for certain application areas. These statements about suitability are based on our knowledge and experience of typical requirements concerning the areas, serve as general guidance and cannot be estimated as binding statements about the suitability for a customer application. The responsibility for the applicability and use in a particular customer design is always solely within the authority of the customer. Due to this fact it is up to the customer to evaluate, where appropriate to investigate and decide whether the device with the specific product characteristics described in the product specification is valid and suitable for the respective customer application or not.

2. Customer Responsibility related to Specific, in particular Safety-Relevant Applications

It has to be clearly pointed out that the possibility of a malfunction of electronic components or failure before the end of the usual lifetime cannot be completely eliminated in the current state of the art, even if the products are operated within the range of the specifications.
In certain customer applications requiring a very high level of safety and especially in customer applications in which the malfunction or failure of an electronic component could endanger human life or health it must be ensured by most advanced technological aid of suitable design of the customer application that no injury or damage is caused to third parties in the event of malfunction or failure of an electronic component. Therefore, customer is cautioned to verify that data sheets are current before placing orders. The current data sheets can be downloaded at www.we-online.com.

3. Best Care and Attention

Any product-specific notes, cautions and warnings must be strictly observed. Any disregard will result in the loss of warranty.

4. Customer Support for Product Specifications

Some products within the product range may contain substances which are subject to restrictions in certain jurisdictions in order to serve specific technical requirements. Necessary information is available on request. In this case the field sales engineer or the internal sales person in charge should be contacted who will be happy to support in this matter.

5. Product R&D

Due to constant product improvement product specifications may change from time to time. As a standard reporting procedure of the Product Change Notification (PCN) according to the JEDEC-Standard inform about minor and major changes. In case of further queries regarding the PCN, the field sales engineer or the internal sales person in charge should be contacted. The basic responsibility of the customer as per Section 1 and 2 remains unaffected.

6. Product Life Cycle

Due to technical progress and economical evaluation we also reserve the right to discontinue production and delivery of products. As a standard reporting procedure of the Product Termination Notification (PTN) according to the JEDEC-Standard we will inform at an early stage about inevitable product discontinuance. According to this we cannot guarantee that all products within our product range will always be available. Therefore it needs to be verified with the field sales engineer or the internal sales person in charge about the current product availability expectancy before or when the product for application design-in disposal is considered. The approach named above does not apply in the case of individual agreements deviating from the foregoing for customer-specific products.

7. Property Rights

All the rights for contractual products produced by Würth Elektronik eiSos GmbH & Co. KG on the basis of ideas, development contracts as well as models or templates that are subject to copyright, patent or commercial protection supplied to the customer will remain with Würth Elektronik eiSos GmbH & Co. KG. Würth Elektronik eiSos GmbH & Co. KG does not warrant or represent that any license, either expressed or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, application, or process in which Würth Elektronik eiSos GmbH & Co. KG components or services are used.

8. General Terms and Conditions

Unless otherwise agreed in individual contracts, all orders are subject to the current version of the "General Terms and Conditions of Würth Elektronik eiSos Group", last version available at www.we-online.com.

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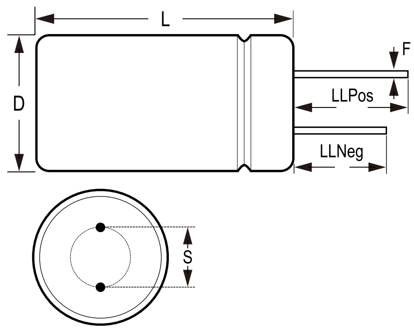
SIZE	REVISION	STATUS	DATE (YYYY-MM-DD)	BUSINESS UNIT	PAGE
10.0 x 20.0	001.000	Valid	2018-11-13	eiCap	9/9

This electronic component has been designed and developed for usage in general electronic equipment only. This product is not authorized for use in equipment where a higher safety standard and reliability standard is especially required or where a failure of the product is reasonably expected to cause severe personal injury or death, unless the parties have executed an agreement specifically governing such use. Moreover Würth Elektronik eiSos GmbH & Co KG products are neither designed nor intended for use in areas such as military, aerospace, aviation, nuclear control, submarine, transportation (automotive control, train control, ship control), transportation signal, disaster prevention, medical, public information network etc.. Würth Elektronik eiSos GmbH & Co KG must be informed about the intent of such usage before the design-in stage. In addition, sufficient reliability evaluation checks for safety must be performed on every electronic component which is used in electrical circuits that require high safety and reliability functions or performance.

KEMET Part Number: HVZ0E106NF
(USCHVZ0E106N00)

KEMET a YAGEO company

HVZ, Supercapacitors, Radial, 10 F, 30%, 2.7 VDC, Wire Leads, Lead Spacing = 5mm



Dimensions	
D	10mm +/-0.5mm
L	35mm +/-2mm
S	5mm +/-0.5mm
LL Negative	15mm MIN
LL Positive	20mm MIN
F	0.6mm NOM

Packaging Specifications	
Lead:	Wire Leads
Weight:	4 g
Packaging:	Bulk, Box
Packaging Quantity:	2000

General Information	
Series:	HVZ
Description:	Radial Cylindrical Double Layer Capacitor
RoHS:	Yes
AEC-Q200:	No

Specifications	
Capacitance:	10 F
Capacitance Tolerance:	30%
Voltage DC:	2.7 VDC
Temperature Range:	-25/+70°C
Rated Temperature:	70°C
Resistance:	100 mOhms (1kHz)
Ripple Current:	8 mAmps (30min)