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FACULDADE DE ENGENHARIA ELÉTRICA E DE COMPUTAÇÃO

Édson Pedro Cecílio Júnior

Capacitor Analyzer
(Capacitance and ESR Precision Meter)

Analisador de Capacitores
(Medidor de Capacitância e ESR de Precisão)

Campinas
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ÉDSON PEDRO CECÍLIO JÚNIOR

CAPACITOR ANALYZER
(CAPACITANCE AND ESR PRECISION METER)

ANALISADOR DE CAPACITORES
(MEDIDOR DE CAPACITÂNCIA E ESR DE PRECISÃO)

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Prof. Dr. Hudson Giovani Zanin (Presidente, FEEC/UNICAMP)
Prof. Dr. Gilmar Barreto (FEEC/UNICAMP)
Dra. Francisca Elenice Rodrigues de Oliveira (USP/USP São Carlos)

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Dedication

I dedicate this work to my beloved little son Pedro, my wife Lidiane, my mother Teresinha and my deceased father Edson.

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Firstly, I would like to thank God for helping me along this long path.

I would also like to express my gratitude to all my family and friends for unconditional support.

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Sometimes, believing in the truth is harder than understanding it.

Abstract

Capacitors are widely used in a plethora of applications, ranging from energy storage systems to switching mode power supplies. Besides its capacitance, every capacitor has some amount of resistance and inductance, since pure elements exist only in theory. Although inductance is generally negligible, resistance plays an important role as far as energy losses and errors in switching circuits are concerned. The total resistance of a capacitor is known as Equivalent Series Resistance – ESR – and its accurate measurement is paramount in order to assess the quality and the conditions of a capacitor for a specific scenario. This work presents a Capacitor Analyzer that can measure both ESR and Capacitance independently and with high precision. The equipment is portable like a Digital Multimeter and its circuitry requires only ordinary components that are easily obtainable. Not only laboratories that develop new kinds of capacitors but also a technician that is fixing a power supply may deeply benefit from this Equipment.

Resumo

Capacitores são amplamente usados em uma grande variedade de aplicações, desde em sistemas de armazenamento de energia até fontes de alimentação chaveadas. Além de sua capacitância intrínseca, todo capacitor tem certa quantidade de resistência e indutância, pois elementos puros só existem na teoria. Embora a indutância seja geralmente desprezível, a resistência desempenha um papel importante nas perdas de energia e em erros em circuitos chaveados. A resistência total de um capacitor é conhecida por Resistência Total Serie – ESR – sigla do inglês Equivalent Series Resistance – e sua medida precisa é primordial para avaliar a qualidade e as condições de um capacitor para um cenário específico. Neste trabalho, desenvolvemos um Analisador de Capacitores que é capaz de medir a ESR e a capacitância de forma independente e com alta precisão. O equipamento é portátil como um Multímetro Digital e seu circuito utiliza apenas componentes comuns de fácil obtenção. Não só laboratórios que desenvolvem novos tipos de capacitores, mas também técnicos que estejam consertando uma fonte de alimentação podem se beneficiar desse equipamento.

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
ADC	Analogue to Digital Converter
DC	Direct Current
DUT	Device under Test
EDLC	Electric Double Layer Capacitor
ESR	Equivalent Series Resistance
GCD	Galvanostatic Charge Discharge
OA	Operational Amplifier
RMS	Root Mean Square

Summary

Chapter 1

Introduction

This work presents the complete design and development of a Capacitor Analyzer. The equipment can measure both capacitance and ESR of electrolytic capacitors with high precision.

In chapter 2, the theoretical fundamentals of capacitance are discussed. The electrical behavior of capacitors driven by relevant kinds of excitations is deeply described and all the necessary mathematical equations are derived. After that, the concept of ESR is introduced and the behavior of capacitors with ESR is completely described as well. After that, the most traditional method to characterize capacitors is presented. It is the Galvanostatic Charge-Discharge Analysis – GCD. In the last chapter data from our system will be contrasted with a commercial CGD equipment to validate our system. Finally, the project is presented with the required and expected specifications.

Chapter 3 emphasizes the need for a microcontroller to carry out the necessary tasks required for the equipment. Microcontroller fundamentals are presented as well as the Arduino concept along with its programming language. The Atmel 328 microcontroller is also presented.

Next, in chapter 4, the theory of measurements of the relevant quantities for the project is deeply investigated. This chapter shows how to measure these quantities digitally and how to find the respective uncertainties.

Chapter 5 presents the complete hardware and software of the system, providing all the design details and calculations. The complete schematics and code are provided.

Eventually, chapter 6 shows the construction of the equipment and the tests that were executed to assess its performance.

Chapter 2
Capacitance and ESR

2.1 Capacitance and Capacitors

A system of insulated electrical conductors can store electrical charge and consequently electrical energy when a voltage is applied to it. The ratio between the stored charge and the potential difference of the system is referred to as its capacitance:

$$C = \frac{Q}{V} \tag{2.1}$$

The unit of capacitance is the Farad (1 F = 1 C/V). The electrical component that is used to provide a predetermined amount of capacitance to a circuit is called a capacitor. Figure 2.1 shows two typical electrolytic capacitors of 10 μF that are commonly used in all kinds of electronic equipment as well as their symbol.

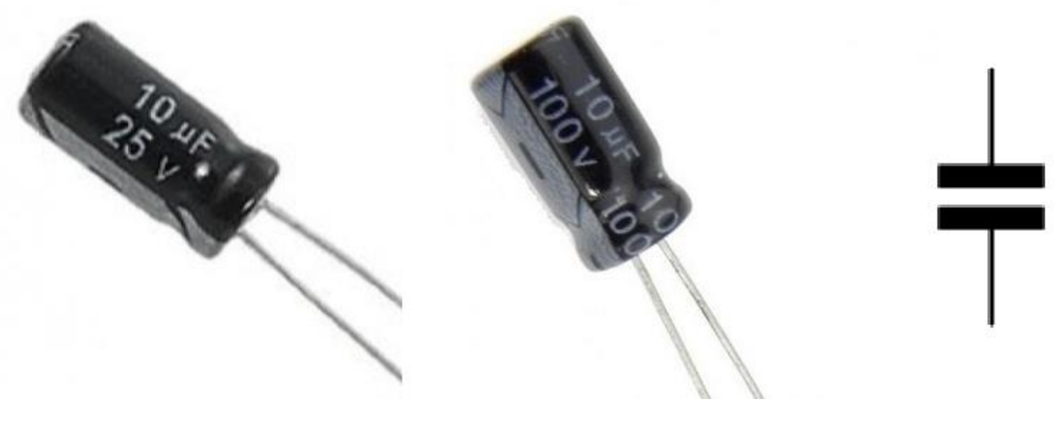

Fig 2.1: Two Electrolytic Capacitors and their symbol

Physically, inside a capacitor, there are two conducting plates insulated by a nonconductive material referred to as a dielectric. The capacitance of a system depends on its geometry. The simplest construction is the parallel plate capacitor show in figure 2.2 which has a capacitance given by:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \tag{2.2}$$

Where $\varepsilon_0$is the electrical permittivity of vacuum – a constant that has a value of 8.85 10^{-12} F/m - ε_r is the relative permittivity of the dielectric – being 1.0 for vacuum and greater than 1.0 for all insulating materials – A is the area of the plates and d is the distance between them.

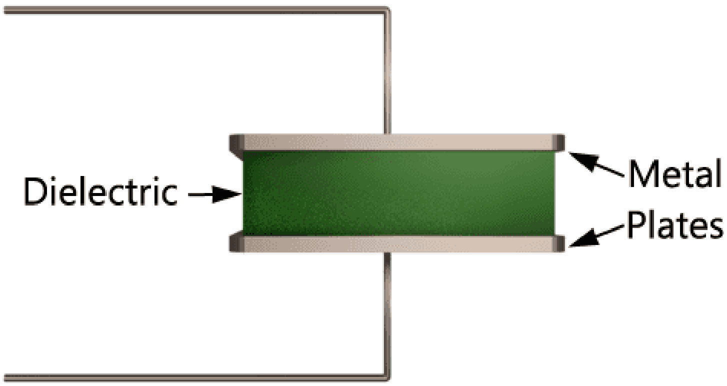

Fig 2.2: Parallel Plate Capacitor

It is clear from this equation that if great capacitances are necessary, dielectrics with big relative permittivity must be used, as well as conducting plates with big areas and small distances of separation between them. Although this equation holds only for the case of a plane capacitor, the fact that big permittivity dielectrics and plates with big areas and small separation leads to big capacitances is general and it holds for any capacitive system.

When a capacitor is charged, an amount of electrical energy is stored in it due to its electrical field. From the definition of voltage:

$$v = \frac{dw}{dq} \;\rightarrow\; dw = v.dq$$

For a capacitor, $q = Cv$ and consequently, $dq = Cdv$. Thus:

$$dw = C.v.dv$$

When a capacitor that is initially discharged (V=0) is charged up to voltage V, the work done and also the energy stored in the element will be:

$$E = \int dw = \int_0^V Cv.dv$$

Finally, the amount of stored energy in a capacitor in Joules is given by:

$$E = \frac{CV^2}{2} \tag{2.3}$$

Thus, if a great amount of stored energy is necessary, both great capacitance and great voltage are required. However, every capacitor has a maximum voltage that can be applied to it – its working voltage – that also depends on both the maximum voltage that the dielectric can withstand, that is, the electric breakdown and also the distances involved.

Observe that whereas the first capacitor in figure 2.1 has a working voltage of 25V, the second one has a working voltage four times greater – 100V. Although they have the same capacitance of 10 µF, the second capacitor can store sixteen times as much energy as the first one, if they are charged up to their respective limits, since energy is proportional to the square of the voltage.

There are many types of capacitors: for small capacitances in the order of pico Farad and nano Farad, its dielectric can be mica, paper, plastic film, glass or ceramic material. These are referred to as electrostatic capacitors. Electrolytic capacitors were developed to achieve higher capacitances, in the order of micro Farads. For huge capacitances, in the order of Farads, supercapacitors or electrochemical capacitors are being developed.

Capacitors have a huge number of applications in all kinds of electrical and electronic circuits such as: smoothing the output of rectifiers in DC power supplies, voltage multipliers, charge pumps, coupling AC signals, decoupling sections of a circuit, signal filters of all kinds (high pass, low pass, band pass, notch), noise filters, tuned circuits, oscillators, power factor correction and motor start. Moreover, after the development of supercapacitors, they are also used as high energy storage elements. In this application, they are used along with a battery, especially in electric vehicles supplying high currents when necessary.

2.2 Electrical Behavior of Ideal Capacitors

Every electric component has a cause-effect relationship that is, a mathematical expression involving the voltage applied to it and the current that flows through it. For a resistor, this relationship is well-known:

$$i = \frac{v}{R} \tag{2.4}$$

This means that the current is directly proportional to the voltage in a resistor. However, in an ideal capacitor, the cause-effect relationship is different:

$$C = \frac{q}{v} \rightarrow q = Cv \rightarrow dq = Cdv \rightarrow \frac{dq}{dt} = C\frac{dv}{dt}$$

Finally:

$$i = C\frac{dv}{dt} \tag{2.5}$$

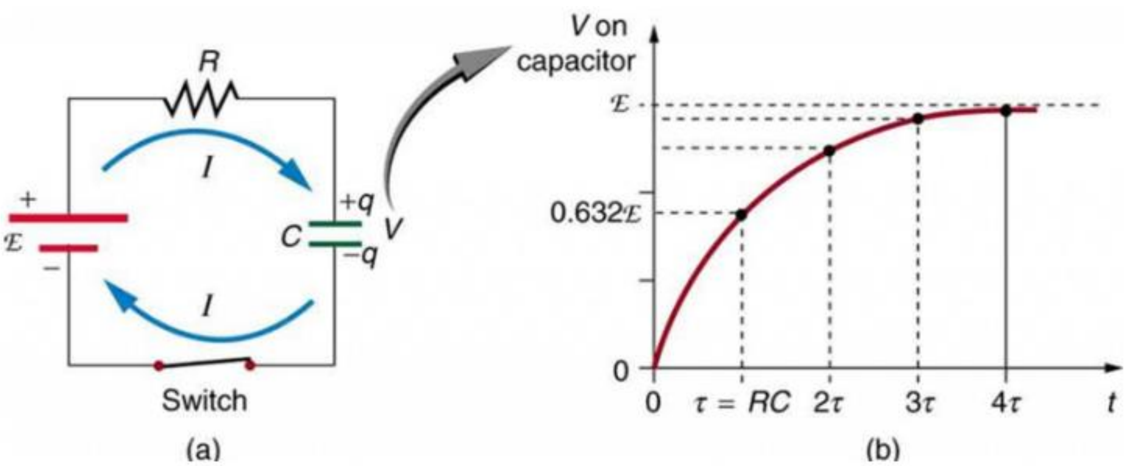

Fig 2.3: RC circuit with DC voltage excitation and its response

And conversely:

$$v = \frac{1}{C}\int i\,dt \tag{2.6}$$

This means that the current that flows through a capacitor is directly proportional to the derivative of the voltage. This also means that an abrupt change in a capacitor voltage is prohibited (capacitor voltage must be continuous), that is, when switching on a circuit with a capacitor occurs, at time t_0:

$$V_c(t_0+) = V_c(t_0-) \tag{2.7}$$

If an ideal capacitor, initially discharged, in series with a resistor is connected to a DC voltage supply, as shown in figure 2.3a, Kirchhoff's law states that:

$$V_c + V_R = E$$

After some algebra,

$$\frac{dq}{dt} + \frac{q}{RC} = \frac{E}{R} \tag{2.8}$$

After solving this first-order differential equation, the voltage on the capacitor is given by:

$$V_c = E\left(1 - e^{-\frac{t}{RC}}\right) \tag{2.9}$$

This classical result states that the capacitor voltage increases exponentially as time goes by, as it is shown in figure 2.3b, with a time constant τ given by the product of R and C.

Whereas a voltage source produces an exponential response that is not so easy to analyze, a current source produces a much more convenient response. Figure 2.4a shows an ideal capacitor, initially discharged, being driven by a DC current source. The switch is closed when $t = t_0$.

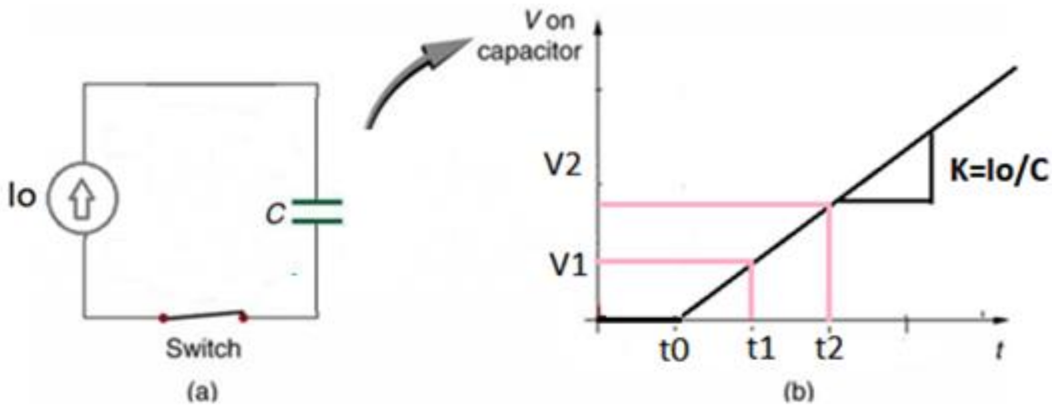

Fig 2.4 – An ideal capacitor with DC current excitation and its response

Using the capacitor equation in integral form (2.6), setting the initial conditions and respecting the voltage continuity requirement (2.7), the voltage on the capacitor is given by:

$$V_c = \begin{cases} 0 & if\ (t < t_0) \\ \frac{I_0}{C}(t - t_0) & if\ \ (t \geq t_0) \end{cases} \tag{2.10}$$

This result shows that the voltage of a capacitor that is driven by a DC current source is a ramp, that is, it is an inclined straight line, as shown in figure 2.5b, with slope K given by:

$$K = \frac{I_0}{C} \tag{2.11}$$

When it comes to capacitance measurements, using a current source rather than a voltage source makes analysis much easier. Instead of working with exponential behaviors, a measurement instrument would deal with a straight line that has a constant slope.

The voltage ramp slope can be determined as the ratio between the voltage variation and time variation, that is:

$$K = \frac{\Delta V}{\Delta t} = \frac{V_2 - V_1}{t_2 - t_1} \tag{2.12}$$

Finally, the capacitance can be readily determined as:

$$C = \frac{I_0}{K} \tag{2.13}$$

Figure 2.5a shows now a pure capacitor connected to an AC voltage power supply. The voltage applied to the component can be mathematically described as:

$$v(t) = V_0 \sin(\omega t) \tag{2.14}$$

Where ω is the angular frequency given by:

$$\omega = 2\pi f \tag{2.15}$$

The current that will flow on the circuit, after the initial transitory period, is given by:

$$i = C\frac{dv}{dt} = CV_0\omega\cos(\omega t)$$

Using trigonometric properties and rearranging:

$$i = \frac{V_0}{\frac{1}{\omega C}}\sin(\omega t + 90°) \tag{2.16}$$

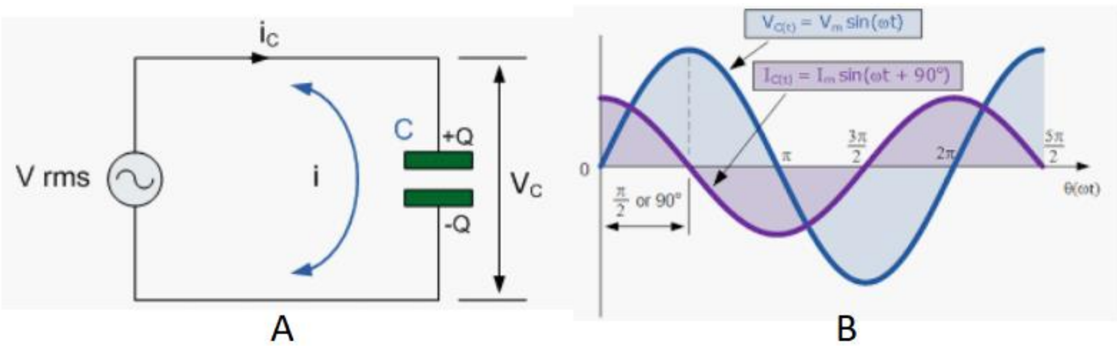

Fig 2.5 – A capacitor that is driven by an AC voltage and its response

The current will have the same form of the voltage, a sinusoid, but leading it by 90 degrees, as shown in figure 2.5b.

As far as measurements are concerned, if peak values are measured:

$$V_{max} = V_0 \tag{2.17}$$

$$I_{max} = \frac{V_0}{\frac{1}{\omega C}} \tag{2.18}$$

If RMS values are measured:

$$V_{rms} = \frac{V_0}{\sqrt{2}} \tag{2.19}$$

$$I_{rms} = \frac{\frac{V_0}{\sqrt{2}}}{\omega C} \tag{2.20}$$

Either way, the ratio between these quantities will be:

$$\frac{V_{max}}{I_{max}} = \frac{V_{rms}}{I_{rms}} = \frac{1}{\omega C} = X_c \tag{2.21}$$

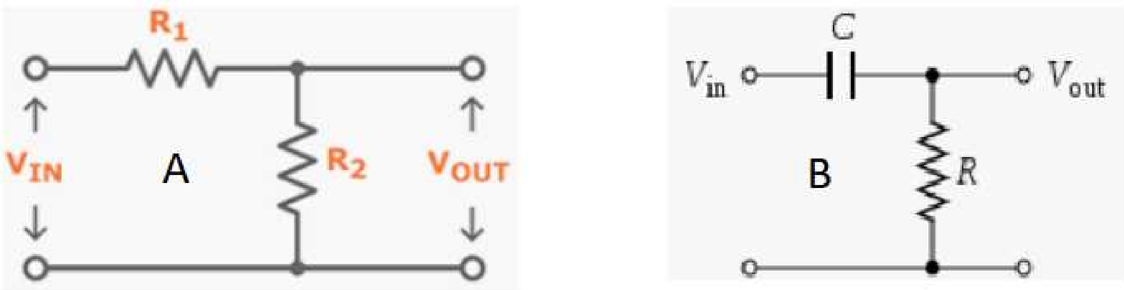

Fig 2.6 – Voltage Dividers

This quantity is called capacitive reactance and its symbol is X_c. It is the "resistance" a capacitor has for alternating voltage. Whereas a resistor has a resistance that is fixed and independent of frequency, Capacitive Reactance depends on the frequency: the greater the frequency is, the smaller the reactance is and consequently more current will flow through the capacitor.

Finally, in figure 2.6a there is a classical resistive voltage divider that comprises two resistors. The output voltage will be a fraction of the input voltage, that is:

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in} \tag{2.22}$$

This relation holds for DC or AC excitations. For AC voltages V_{in} and V_{out} must be both peak or both rms values. The ratio between V_{in} and V_{out} is the attenuation factor and it will be symbolized by F.

$$\frac{V_{in}}{V_{out}} = F \tag{2.23}$$

It is important to note that F is always greater or equal than one:

$$F \geq 1 \tag{2.24}$$

If V_{in} and V_{out} are measured, it is possible to calculate F and, as long as R_2 is known, it is possible to determine R_1:

$$R_1 = (F - 1)R_2 \tag{2.25}$$

In figure 2.6b, there is a voltage divider that uses a capacitor and a resistor, instead of two resistors, driven by an AC voltage.

In this case, the relationship between V_{in} and V_{out} is:

$$V_{out} = \frac{R}{\sqrt{R^2 + {X_c}^2}} V_{in} \tag{2.26}$$

In this case, the circuit is a frequency-dependent voltage divider, also known as a high pass filter. Signals with high frequency are delivered to the output whereas low frequency signals are attenuated.

2.3 ESR and the Real Capacitor

An ideal capacitor, as its name suggests, does not exist in practice. A real capacitor has, besides its capacitance, an amount of resistance, inductance and even a small noise voltage. Thus, a practical component has a model that it is quite different from the ideal. This model can range from the simplest one that take one feature at a time to the most complicate and complete ones that consider many characteristics simultaneously.

In this work, the main interest is on the global series resistance that a capacitor has, namely Equivalent Series Resistance (ESR). This resistance arises due to leads, electrodes and dielectric contributions. Figure 2.7 shows the C + ESR model for a real capacitor that will be used throughout this work.

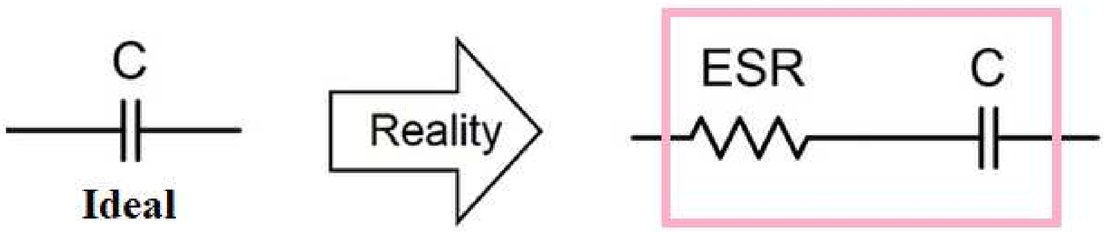

Fig 2.7 – C + ESR model for a real capacitor

High ESR values are undesirable because the higher the ESR is, the farther a real capacitor is from its ideal correspondent. This leads to many issues, such as:

- Switching Mode Power Supplies and other digital circuits tend to act up when capacitors have their ESR increased because of extended usage.

- When used as storage energy elements, capacitors (mainly supercapacitors), when they are supplying energy (discharging), ESR acts as internal resistance, limiting the maximum power that can be delivered to the load.

Measuring ESR with precision and accuracy is paramount not only for a technician that is servicing a piece of equipment but also for research laboratories that develop and manufacture capacitors as ESR can be used as a quality factor for the process.

It is crucial to notice that it is impossible to have access to Capacitance and ESR individually as it is shown in figure 2.8a. Capacitance and ESR are “bound” inside the component besides being only a mathematical model. As shown in figure 2.8b, what can be done is to measure the voltage across the entire component, with a voltmeter. Keep in mind that the voltage measured on the capacitor (V_c) is the sum of the voltages on the capacitance (V_{cap}) and the resistance (V_{ESR}), that is:

$$V_{meaured\ on\ cap} = V_c = V_{CAP} + V_{ESR} \tag{2.27}$$

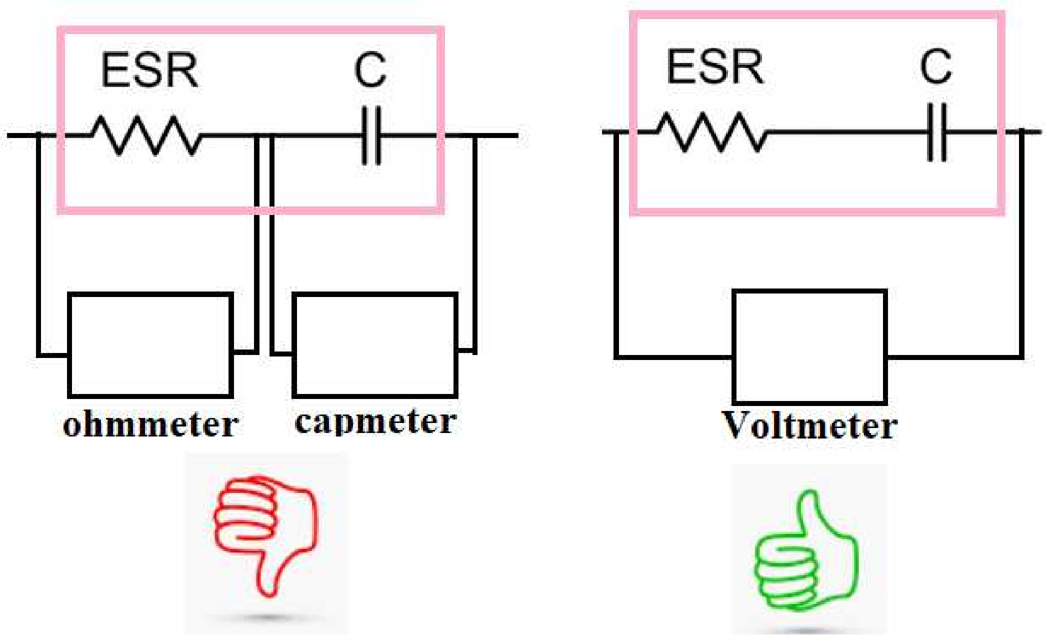

Fig 2.8 – Individual access to ESR and Capacitance is impossible!

2.4 Electrical Behavior of Real Capacitors

Figure 2.9a shows an initially discharged real capacitor with ESR connected to a current source. At time $t=t_0$ the switch is closed. The capacitor comprises its capacitance and ESR and the voltage on the entire component is the sum of the voltages on these two elements. The voltage solely on the capacitance is a ramp, exactly as seen before, and the voltage solely on the ESR is a constant, given by ohm's law. Thus, the total voltage on the capacitor is:

$$V_c = \begin{cases} 0 & if\ (t < t_0) \\ \frac{I_0}{C}(t - t_0) + ESR.I_0 & if\ \ (t \geq t_0) \end{cases} \tag{2.28}$$

Figure 2.9b shows the response of the circuit. When the switch is closed, at t = t_0, there is a discontinuity in the capacitor voltage, given by ESR.I_0. After this “jump”, the total voltage on the capacitor increases linearly, with the same constant slope of a pure capacitor with capacitance C (exactly like equation 2.11), that is:

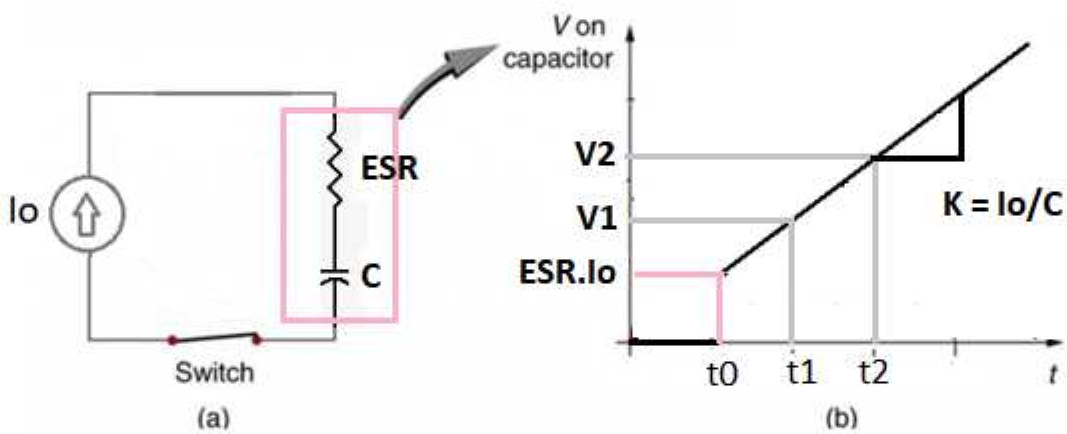

Fig 2.9 - A real capacitor with DC current excitation and its response

$$K = \frac{I_0}{C} \tag{2.29}$$

If voltage and time variations are measured, as long as the measurements are made after the jump discontinuity, it is possible to find K as:

$$K = \frac{\Delta V}{\Delta t} = \frac{V_2 - V_1}{t_2 - t_1} \tag{2.30}$$

And finally, it is possible to determine the capacitance, independently of the ESR, as:

$$C = \frac{I_0}{K} \tag{2.31}$$

Eventually, figure 2.10 shows a real capacitor (C + ESR) connected to a fixed resistor R_0. An AC voltage is applied (V_{in}) and the AC voltage on R_0 is the output (V_{out}). This circuit is a frequency-dependent voltage divider configured as a high pass filter.

The ratio between V_{in} and V_{out} will still be called F, that is:

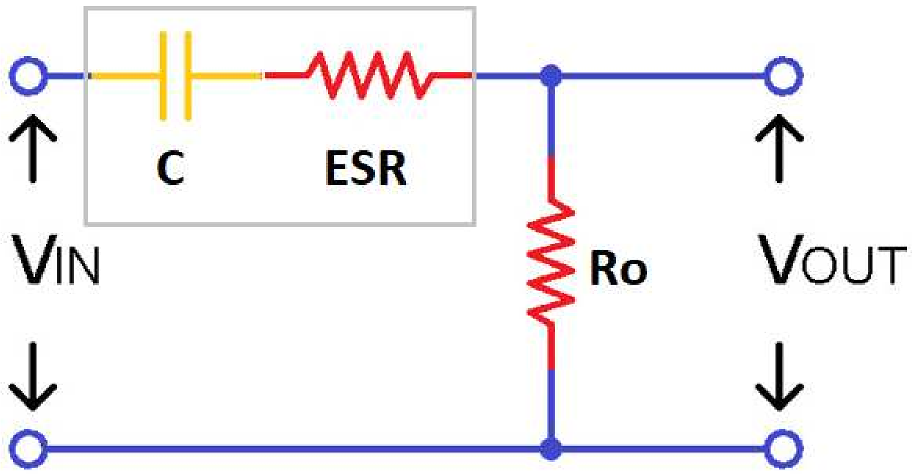

Fig 2.10 –AC Voltage Divider with a real capacitor

$$\frac{V_{in}}{V_{out}} = F \tag{2.32}$$

The relationship between V_{in} and V_{out} depends on the values of ESR, X_c of the capacitor at the AC excitation frequency and R_0:

$$V_{out} = \frac{R_0}{\sqrt{X_c^2 + (R_0 + ESR)^2}} V_{in} \tag{2.33}$$

Using F for the ratio between the voltages and after some mathematical manipulations, it can be shown that in order to determine ESR, it is necessary to solve the following quadratic equation:

$$ESR^2 + 2R_0ESR + (R_0^2 - F^2R_0^2 + X_c^2) = 0 \tag{2.34}$$

After using the quadratic formula, making some simplifications, and considering only the positive root, it is possible to show that:

$$ESR = \sqrt{F^2R_0^2 - X_c^2} - R_0 \tag{2.35}$$

Notice that if $F.R_0$ is much greater than X_c, the circuit behaves as a resistive voltage divider, that is:

$$ESR = (F - 1)R_0 \tag{2.36}$$

When:

$$F.R_0 \gg X_C \tag{2.37}$$

This means that, if F is determined by measuring the input and output voltages on the circuit and if R_0, C and the frequency f of the AC exciting voltages are known, it is possible to determine the ESR of the capacitor.

2.5 Characterizing a Capacitor: GCD

Researchers are always trying to develop new kinds of capacitors and improve the performance of the ones that already exist. To evaluate the quality of the device by measuring its electrical characteristics, there is a bunch of characterization methods that can be used. Each component has a typical response – a signature.For Capacitors, one of the methods that are frequently used is Galvanostatic Charge Discharge (GCD).

In this method, a current source is used to drive the device under test (DUT) and the voltage developed on it is recorded, as it is shown in Figure 2.11. Finally, the result of the analysis is a chart that shows how the voltage behaves with time.

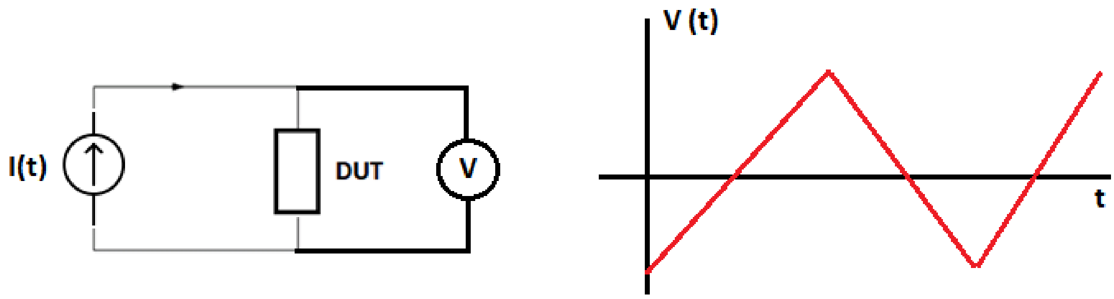

Figure 2.11- A GVD Setup and a typical result

The current that drives the DUT has a constant value $+I_0$ during half the period and $-I_0$ during the other half as Figure 2.12a shows. For a simple case of a pure Capacitor with capacitance C, the voltage developed on it is:

$$v = \frac{1}{C}\int i\,dt \tag{3.6}$$

For a constant current $\pm I_0$, equation 3.6 becomes:

$$v = \pm\frac{I_0}{C}t + K \tag{3.7}$$

Where K is a constant. It also important to point out that the voltage on the capacitor cannot change abruptly on switching points, that is, if a switching happens at t_0:

$$V_c(t_0 +) = V_c(t_0 -) \tag{3.8}$$

Initially, the capacitor is discharged, which is V_c=0. When the current $+I_0$ starts to flow at t=0, Vc must be continuous which leads to the following voltage for the capacitor, between t=0 and t=T/2:

$$v = +\frac{I_0}{C}t \tag{3.9}$$

This is a straight line with slope I_0/C that starts at zero volts and reaches I_0T/C. When t=T/2, the current abruptly changes its polarity to $-I_0$. As the voltage on the capacitor cannot change abruptly, its voltage will necessarily be:

$$v = -\frac{I_0}{C}t + \frac{I_0T}{C} \tag{3.10}$$

This is also a straight line with slope $-I_0/C$ that starts at I_0T/C and reaches zero. Figure 2.12b shows this result.

In Summary, the charge-discharge plot for a pure capacitor is a triangular voltage and its capacitance can be determined by employing the voltage slope as long as the driving current is known.

If a Capacitor with ESR is driven by the same current of Figure 2.12a, the answer will be a little bit different. In this case, the measured voltage on the DUT will be the sum of the voltages on the capacitance and ESR, that is:

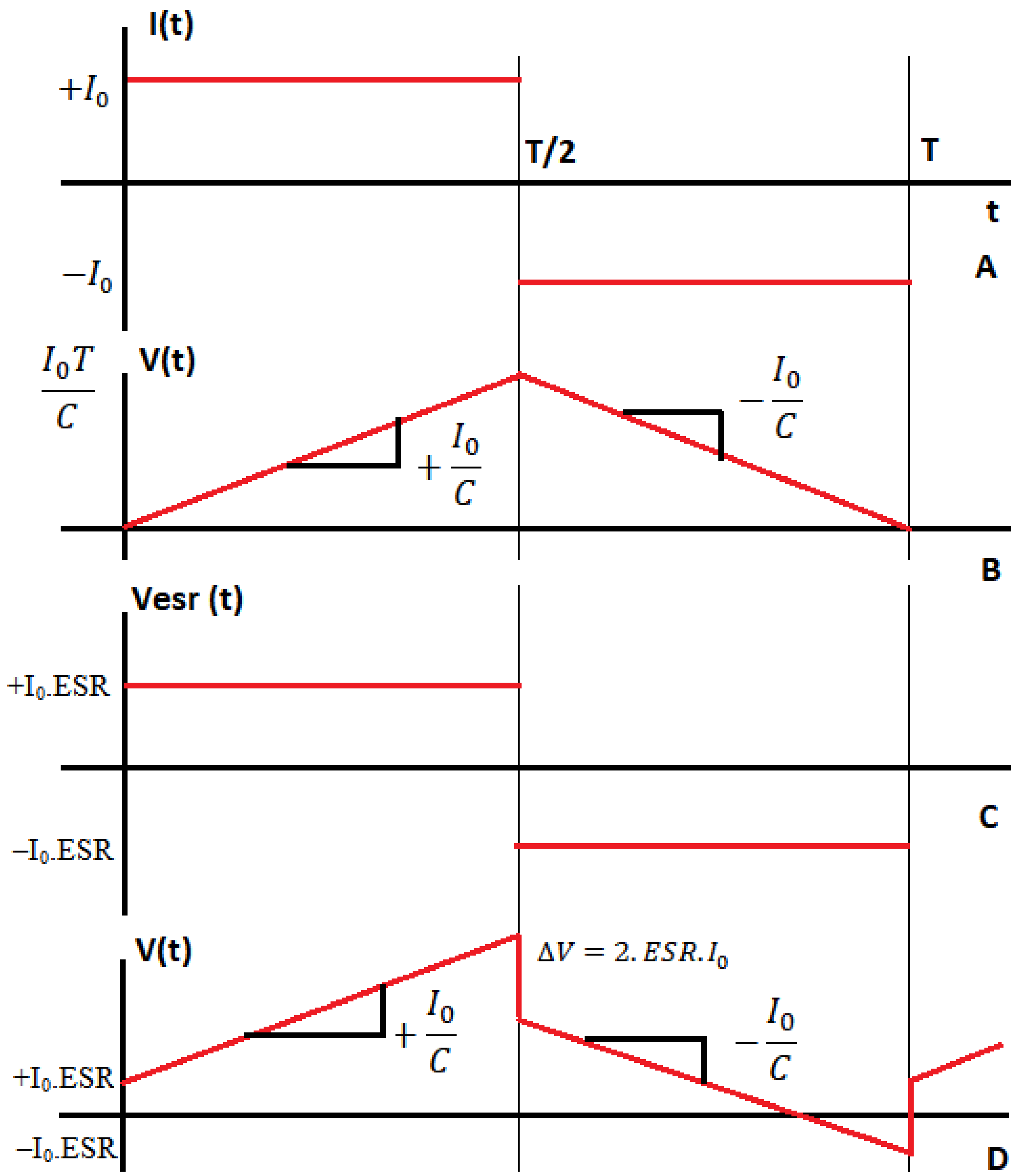

Figure 2.12 – GVD Plots

$$v = V_C + V_{ESR} \tag{3.11}$$

But the current that will flow through C and ESR is the same since they are in series and equals the driving current of the current source. The voltage on the capacitive part of the DUT will be the same as if it were a pure capacitor – the voltage shown in Figure 2.12b. The voltage on the resistive part – the ESR – will be, by Ohm's law, $+I_0$.ESR for t=0 to t=T/2 and $–I_0$.ESR for t=T/2 to t=T, as it is shown in Figure 3.4c. Eventually, the total voltage on the DUT will be the sum of the voltages shown in Figure 2.12b and 2.12c, that is, the plot shown in Figure 2.12d. The slope of the lines are still $\pm I_0/C$ and at the switching times from $+I_0$ to $-I_0$, the voltage will suffer a drop of:

$$\Delta V = 2.ESR.I_0 \tag{3.12}$$

In conclusion, the slope of the voltage plot can be used to determine the capacitance and the voltage drop can be used to determine the ESR in a typical Capacitor with ESR.

3.2 The aim of this work: A Precision Capacitor Analyzer

The characterization method of GCD is capable of determining the capacitance and ESR of a capacitor with high reliability but there are some drawbacks:

- The equipment is expansive;
- The results are not direct: the user must interpret the Voltage plot and make all the necessary calculations to determine C and ESR;
- The equipment is not portable;

The main purpose of this work is to develop a Capacitor Analyzer: a portable, low-cost, high-precision Capacitance and ESR meter that shows the results directly on a display, similar to a Digital Multimeter. The device must be able to measure both Capacitance and ESR independently with good accuracy. A satisfactory error study will also be done in order to determine the uncertainty of these measurements.

As far as the capacitance range is concerned, the equipment will be able to determine the capacitance of all electrolytic capacitors, typically in the range of 1.0 μF to 20.000 μF. The ESR range will be in the order of 0.1 ohm to 100 ohms.

The principle of operation of the equipment is based on what was discussed so far. A precision current source is connected to the DUT. There is a relay that keeps the DUT short-circuited and discharged when it is OFF. The relay is ordered to turn ON but there is a mechanical delay on its contacts T_0 between the order and the actual switching. If the voltage on the capacitor starts to be measured after T_0 the jump-discontinuity due to ESR will be avoided. By measuring the speed at which the voltage on the capacitor increases, it is possible to determine the Capacitance of the DUT independently of its ESR. As the range of Capacitance to be measured is too wide, two scales will be necessary and a relay will be responsible to change the currents for each scale.

After measuring the Capacitance, another relay disconnects the DUT from the current source and connects it to a voltage divider driven by an AC sinusoidal generator with low output impedance. By measuring the Peak AC voltages on the input and output of the voltage divider, it is possible to determine the ESR of the DUT.

Chapter 3
Microcontroller Based Instruments

3.1 The need for a microcontroller

In the last chapter, the principle of operation of the Capacitor Analyzer was comprehensively explained and as it was seen, the equipment must be able to perform many different kinds of intricate tasks.

First of all, the equipment is supposed to perform a set of procedures in a specific sequence. Secondly, it has to measure many quantities with a good degree of precision, such as DC constant voltages, DC varying voltages, peak values of AC sinusoidal voltages, time intervals and frequency. Moreover, many intricate calculations must be done with these measurements such as all the basic kinds of operations with rational numbers: addition, subtraction, multiplications, division, arithmetical mean, comparisons, maxima and minima of a set of numbers, power and square root. In order to perform some of these calculations, a great amount of data must be processed and stored leading to the need for memory resources. Another task that is required is the commutation of some relays in order to connect the DUT into different sections of the circuit as well as shorting its leads to discharge it. Some of these commutations must be performed with a high timing precision. Finally, many messages and values are supposed to be shown to the user during the measurement.

It stands to reason that it would be very difficult or even impossible to do all these tasks with a purely analog device. In cases like that, it is advisable to use a microcontroller that will manage the sequence of actions, measure the quantities, store and process the data, show the information to the user as well as an analog auxiliary circuitry that is responsible for generating the necessary signals for the unit.

3.2 Microcontroller Fundamentals

A microcontroller is a small computer on a single chip. It comprises a microprocessor along with RAM and ROM memory, a serial communication interface, a Timer and programmable INPUT/OUTPUT ports that control some or all of the functions of an electronic device or system as Figure 3.1a shows. A program that is transferred into its internal program memory has the instructions that dictate what the microcontroller is supposed to do.

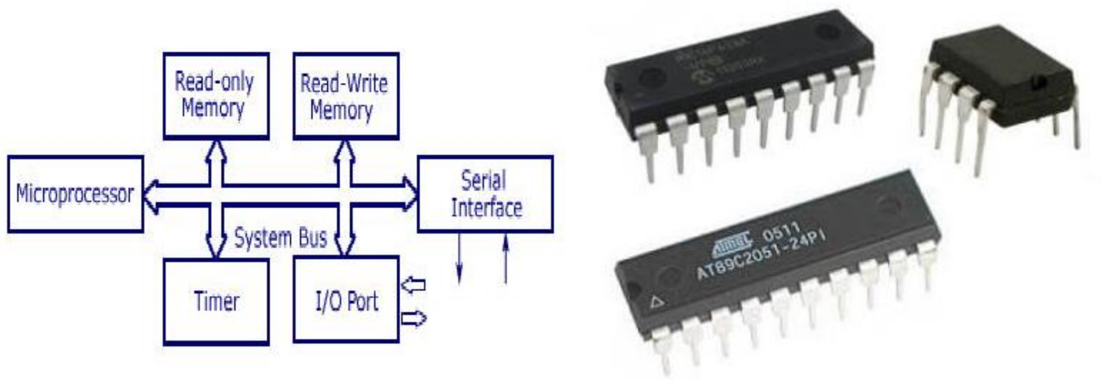

Fig 3.1 – Microcontrollers Internally and Externally

Physically, a microcontroller is an integrated circuit with a bunch of pins, each one with a different function. There are also many kinds and sizes of microcontrollers with different numbers and types of inputs and outputs, memory capability, speed and processor size as Figure 3.1b shows. The choice of a specific chip depends on the project demands.

A microcontroller alone is not able to do useful things. In fact, it is not even able to work at all. Firstly, the device must be powered with a proper stabilized voltage and a convenient quartz crystal must be connected into the oscillator terminals in order to establish the CLOCK signal that will provide the rhythm to the processor. Secondly, its inputs and outputs must be properly connected to the external circuits so that all the information can flow into and out of the microprocessor. Finally, the communication interface must be properly configured and a program with all the instructions based on everything that is connected to the unit must be written, compiled and transferred to the device using the communication pins.

To make things easier, some development kits were created. These kits comprise a board with the microcontroller itself and all the necessary basic hardware already connected to it. The program can be written in C language in an appropriate programming environment and then transferred via USB port to the microcontroller on the board.

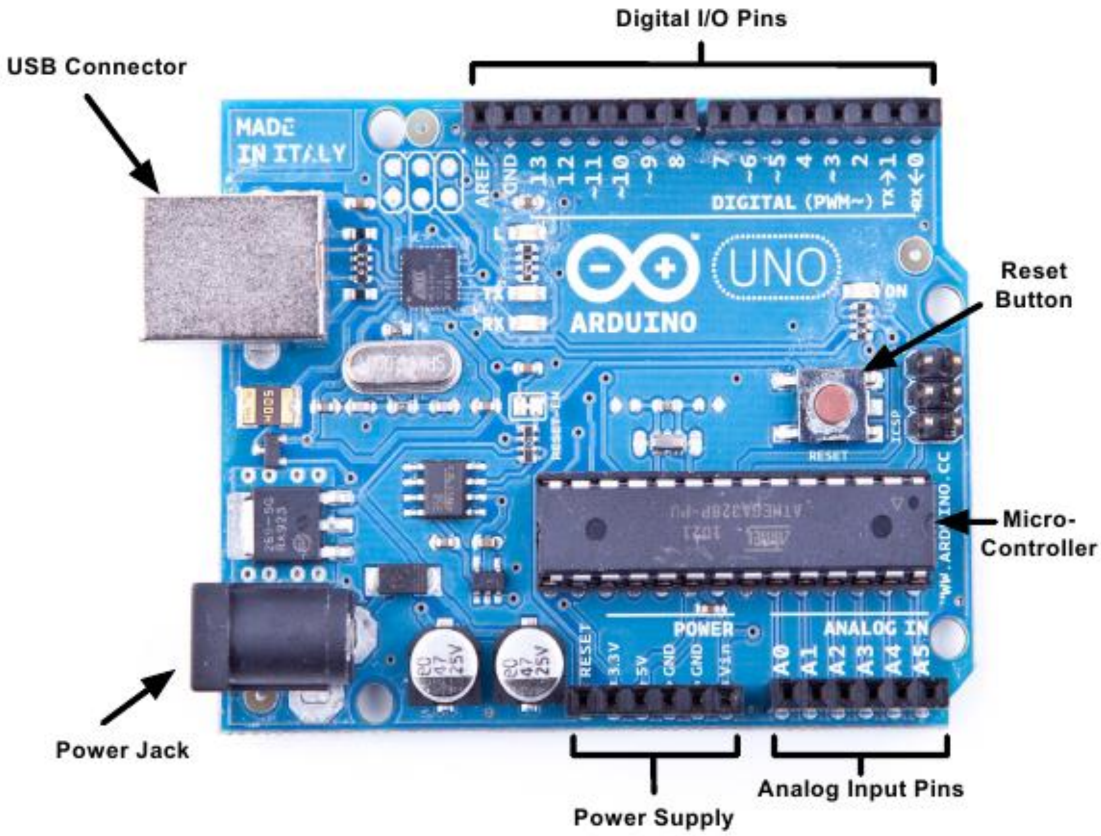

Fig 3.2 – Arduino UNO Board

One of these development kits became very popular. The name of this famous project is ARDUINO. It has many kinds of boards with all kinds of microprocessors ranging from very simple ones that are very limited to extremely powerful units. All the basic hardware functionalities are included. Figure 3.2 shows one of the most famous ARDUINO boards, the ARDUINO UNO, as well as its main connectors, microcontroller and controls.

The program for an Arduino Board is written in its own development environment, using its own ARDUINO language – a variation of C language with some handy functions – compiled and then transferred to the board via USB port. Figure 3.3 shows the appearance of the programming environment along with an extremely simple program that makes an LED flash using some structures and functions of the Arduino language. All the software, references and drivers for Arduino can be downloaded on the internet at arduino.cc.

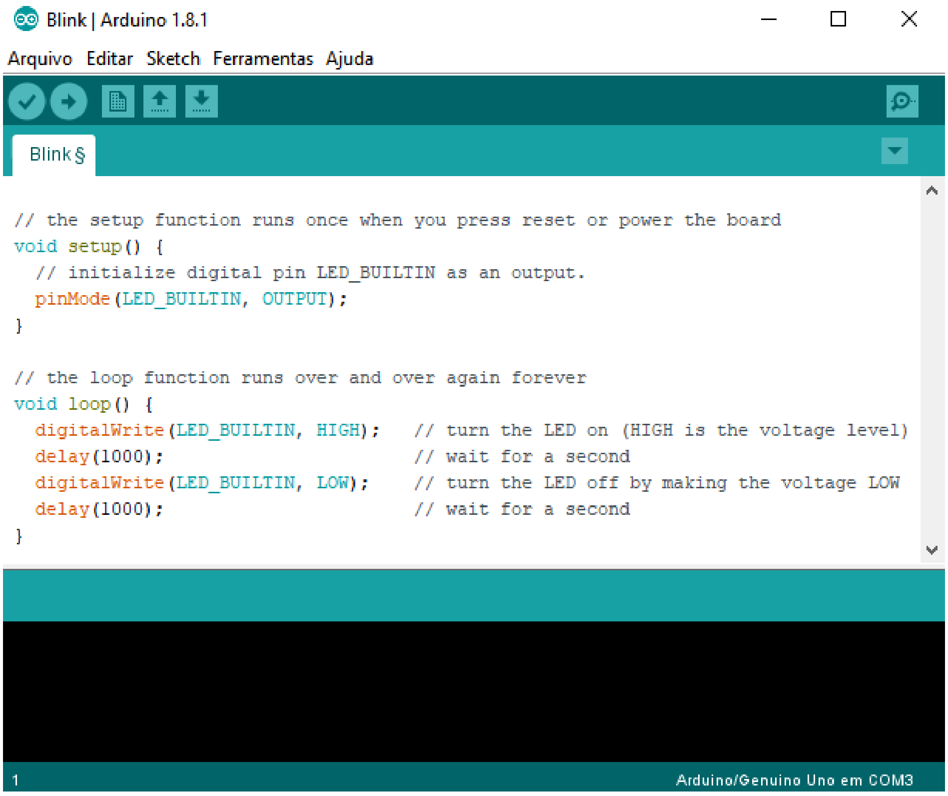

Fig 3.3 – Arduino Programming Environment

It is possible to use an Arduino board with all the additional hardware and circuits hooked to the board connectors. But is this case, for each equipment, it will be necessary a complete board and this might bring about higher costs to the project. Instead, it is possible to develop a project using an ARDUINO board and as soon as everything is working properly, a printed circuit board can be done and only the microprocessor can be removed from the Arduino board and installed onto the PCB as long as the board provides all the requirements for the microprocessor to work.

The Capacitor Analyzer started with an ARDUINO UNO board at first and after the development period was successful, the microcontroller alone was installed on its PCB board. The ARDUINO UNO board comes with a 28 pin microcontroller manufactured by ATMEL called ATMEGA 328P. This microcontroller was the natural choice for the Capacitor Analyzer since the ATMEGA 328P has all the necessary and sufficient functionalities for the project. Figure 4.4 shows its physical appearance and the names for each of its 28 pins. In the next section, the hardware of the microcontroller will be discussed in detail.

3.3 The ATMEGA 328P

The ATMEGA 328P has to be connected to a power supply to work properly. A well-regulated voltage of 5V must be delivered to pin 7. Pins 8 and 22 must be connected to the ground.

Pins 9 and 10 must be connected to an oscillator crystal of 16 MHz to produce the necessary clock signal for the unit. It is advisable to use 10 pF decoupling capacitors in each of these pins.

Pin 1 must be held high through a 10 kΩ pull-up resistor. If it is momentarily grounded, the microcontroller will reset and the program inside it will restart.

Pins 2 and 3 are used to RECEIVE and TRANSMIT data. These pins along with pin 1 and ground can be used to transfer the desired program to the unit by using an ARDUINO UNO board without a microcontroller on its socket.

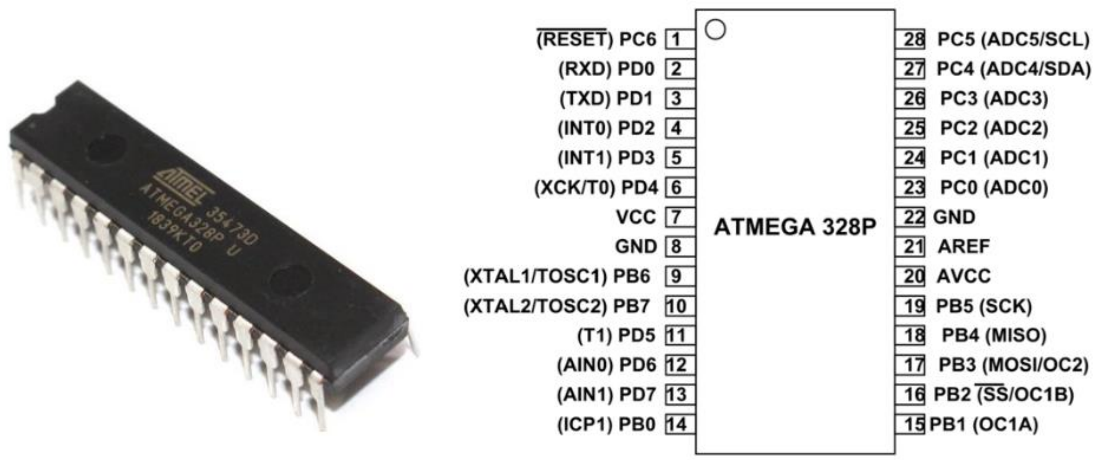

Fig 3.4- ATMEGA 328P and its pins

Pins 4 to 6 and 11 to 19 (a total of 12 pins) can be used as digital inputs or digital outputs. This can be selected via software. Digital inputs are useful to verify if a voltage at a point of the circuit is VCC or 0V whereas a digital output can be used to turn an external device on or off. The maximum output current for each pin is 40 mA.

Pins 23 to 28 can be used as analog inputs that is, ADC's – analog to digital converters. The ATMEGA 328 has 12 bits of precision. This means that the input voltage will be proportionally converted to a number between 0 and 2^N-1, where N is the number of bits. In this case, the number will range from 0 to 1023.

The ADC must receive power through pin 20 (AVCC) to work properly. This pin must be connected to VCC and a decoupling capacitor is required. Moreover, the

ADC uses a voltage reference to carry out the conversions. This voltage reference will set the input voltage full scale. The default reference voltage is VCC but it is possible to use an external reference for more precision and stability. This reference must be applied to pin 21 (AREF) and a corresponding function must be used on the software to configure this option.

4.4 The ARDUINO Language

In order to write the programs that will instruct the microcontroller, it is convenient to use the ARDUINO Language. It is based on the C language and it is a very intuitive and versatile language.

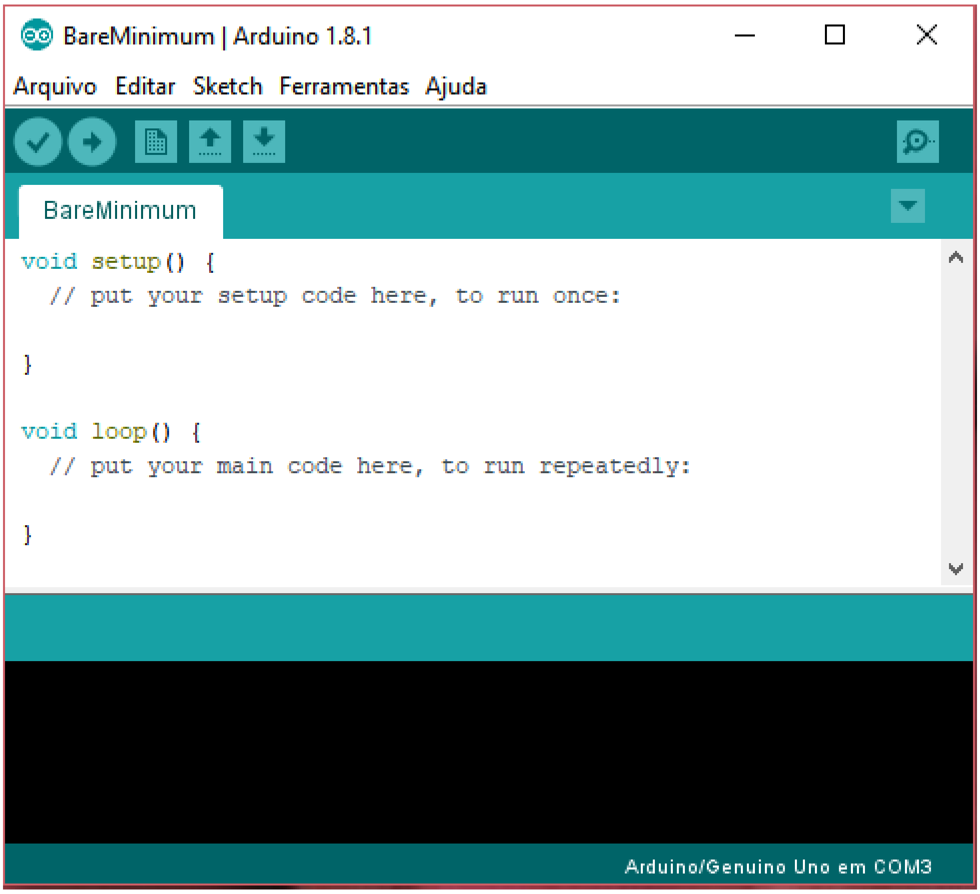

Fig 3.5 – Arduino Bare Minimum

First of all, every program has to bring at least two basic functions (the bare minimum), as Figure 3.5 shows. All the code inside the SETUP function will be executed once right after the circuit starts or restarts whereas the code inside the LOOP function will be executed repeatedly until the circuit is turned off. Incidentally, comments are done by using double forward slashes. Comments are ignored by the compiler.

Variables are created by declaring them using keywords. For integer variables, the word **int** must be used. For Boolean and rational variables, the keywords are **bool** and **float**, respectively. Arrays of variables can also be created and used to store a bunch of data, if necessary.

To carry out the most common mathematical operations such as addition, subtraction, multiplication, division and power, the ubiquitous symbols +,-,*,/,^ are used. For more advanced operations, there are functions to execute the task. For square root, it is possible to use sqrt() with the argument inside the brackets. For sine, for instance, there is the sin() function.

The Arduino Language has all kinds of looping and decision structures that are common to all modern languages. For loops with a pre-determined number of interactions, there is a FOR structure. For example, the next code will calculate the sine of 3.14 radians 100 times:

```
For (int i=0; i<100; i++)
{
        sin (3.14);
}
```

For comparisons, there is an IF/ELSE structure. In the next example, if A>B code 1 will be executed. Otherwise, code 2 will be carried out:

```
If (A>B)
{           "Code 1"     }
Else
{           "Code 2"     }
```

There are also a lot of functions that are used to configure and access the hardware itself such as reading digital and analog inputs, writing values to digital outputs, configure a specific pin as an output and many others.

The user may also write his or her own function that can be called anywhere inside the software.

In order to make things easier, there are also lots of libraries that were written for specific purposes and can be used. If the microcontroller is supposed to communicate to a LCD display, for instance, there is already a ready-to-use library. It is not necessary to write all the code, line by line, to do that. A library can be added to the program by using the keyword #include and saving it in the appropriate folder "libraries" inside the directory where ARDUINO was installed.

Finally, the language also accepts pure C commands and functions. This is useful when the user has to gain access to more specific and advanced features of the microcontroller, generally not supported by the ARDUINO language only.

Chapter 4

Microcontroller Based Measurements

Measuring physical quantities is crucial to get a better understanding of all kinds of phenomena. When a quantity is measured by an instrument, its magnitude is compared with a standard and a number is assigned to it. There is always a degree of uncertainty that must be known in order to characterize the measurement completely. Thus, if a 10% uncertainty ohmmeter displays a resistance of 100 ohms, this means that it is highly likely that the true resistance is inside the interval between 90 ohms and 110 ohms. In this chapter, it will be discussed the principles of electrical measurements and how to calculate the associated uncertainties, especially the ones that are relevant for the Capacitor Analyzer itself.

4.1 Analog Electrical Measurements

In the Electricity and Electronics realm, the basic measurement instrument is the DC voltmeter. It measures the DC voltage between the two points where it is connected as figure 4.1 a shows. Ideally it has infinite impedance and must be connected in parallel with the element that is being measured. The voltage must be reported as the displayed voltage V_0 – the most likely value - plus or minus the uncertainty δV or:

$$V = V_0 \pm \delta V \tag{4.1}$$

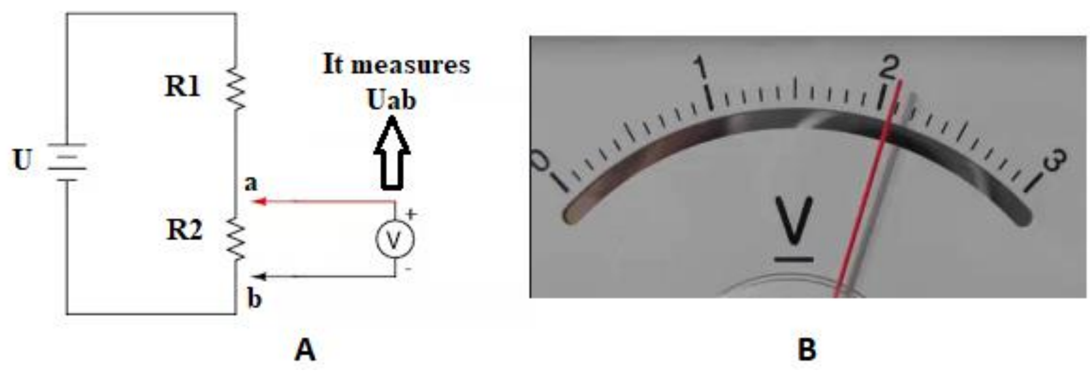

Figure 4.1 – A DC Voltmeter

As the instrument is analog, the uncertainty is defined as half the value of the smallest scale division. Thus, the voltage measured by the voltmeter in figure 4.1 b will be reported as:

$$V = 2.10 \pm 0.05V$$

Interestingly, the measurement of all other electrical quantities derive from the DC voltage measurement, that is, the same DC voltmeter will be used but in a different circuit configuration.

To measure the DC current flowing through an element, a DC voltmeter can be used to measure the voltage V_0 developed on a small known precision resistance R_0 that is connected in series with the element as figure 4.2a and 4.2b shows.

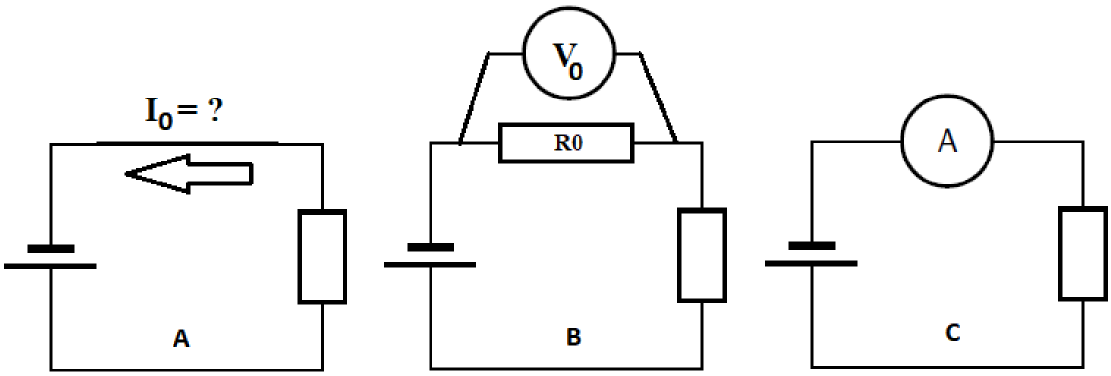

Figure 4.2 – Measuring DC Current

Thus, the current will be determined by using the simple and famous Ohm`s law:

$$I_0 = \frac{V_0}{R_0} \tag{4.2}$$

To avoid using a calculator for every measurement and divide manually the displayed voltage V_0 by the resistance R_0 to determine the current, a new scale can be drawn on the voltmeter, displaying the results – the current – directly, turning it into an ammeter as Figure 4.2 c shows.

The uncertainty in the current depends on the uncertainties in both the voltage and the resistance. When a quantity Z is a mathematical function of, for instance, two other quantities X and Y, the uncertainty in Z, denoted by δZ can be derived as:

$$\delta Z^2 = \left(\frac{\partial Z}{\partial X}\right)^2 \delta X^2 + \left(\frac{\partial Z}{\partial Y}\right)^2 \delta Y^2 \tag{4.3}$$

Where ∂X and ∂Y are the uncertainties in the measured quantities X and Y as long as they are independent.

In this case, the uncertainty in the current is:

$$\delta I^2 = \left(\frac{\partial I}{\partial U}\right)^2 \delta U^2 + \left(\frac{\partial I}{\partial R}\right)^2 \delta R^2$$

After some algebra, it is possible to show that:

$$\left(\frac{\delta I}{I}\right)^2 = \left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta R}{R}\right)^2 \tag{4.4}$$

This last expression states that, the relative uncertainty in the current depends on the quadratic sum of the relative uncertainties in the resistance and in the voltage.

The measured current will be finally reported as:

$$I = I_0 \pm \delta I \tag{4.5}$$

4.2 Digital Electrical Measurements

4.2.1 DC Voltages

In the digital world, the basic meter instrument is the Analog to Digital Converter: the ADC. An ADC converts a DC voltage that is applied to its input into an integer number as Figure 4.3 a shows. Whereas the input voltage is continuous and can vary from zero to a maximum value that depends on a Reference Voltage that is used, the output is discrete and varies accordingly, from zero to a maximum value that depends on the number of bits (resolution) of the ADC. Thus, the voltage is discretized or quantized. Figure 4.3 b shows a typical transfer function for a hypothetical 3-bit

If the number of bits of the ADC is N, the output can vary from zero to 2^{N-1}. The output value 2^N is not reached and would correspond to an input voltage of V_{REF}.

Thus, the relationship between V_{in} and N can be derived by means of a simple proportion:

$$\frac{V_{in}}{V_{REF}} = \frac{N}{2^N}$$

Thus, the number that corresponds to a certain V_{in} that the ADC will return is:

$$N = \frac{V_{in}.\,2^N}{V_{REF}} \tag{4.6}$$

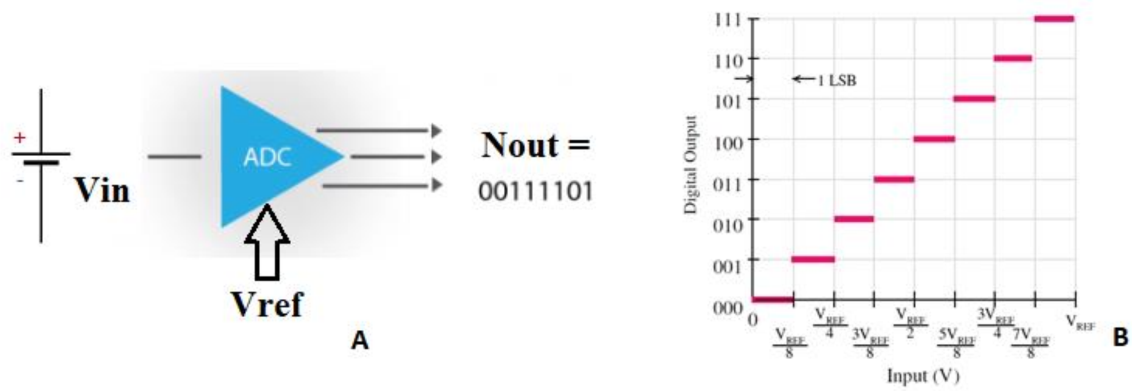

Figure 4.3 – An Analog to Digital Converter and its transfer function

And conversely, if N is known and the corresponding original voltage is desired:

$$V_{in} = \frac{V_{REF}}{2^N}N \tag{4.7}$$

As N is a function of V_{in} and V_{REF}, that is, N = N(V_{in}, V_{REF}), it is crucial to keep V_{REF} as stable as possible to make accurate conversions.

In order to make the output number vary at least one unit, the input voltage must undergo a minimum change. This value is called 1 LSB (one least significant bit) and it is exactly the base of each step in figure 4.3b. It is also the proportionality constant that relates V_{in} and N in Equation 4.7, that is:

$$1LSB = \frac{V_{REF}}{2^N} \tag{4.8}$$

Thus, when a voltage is measured using an ADC, there is always at least an uncertainty due to the quantization process. The total uncertainty takes all sources of uncertainty into account such as quantization, off-set and lack of linearity. The ATMEL 328 has six 10-bit ADC`s with a total uncertainty of $\pm$ 2LSB, according to its handbook.

When the analogRead() Arduino function is called, a measurement is accomplished and the function returns an integer number, according to the applied voltage on its input. It is also possible to select which reference voltage will be used: default 5V supply voltage (which tends to be very poor-regulated), internal reference of 1.1V or an external reference applied on the AREF pin. This selection is made by using the analogReference() Arduino function. The minimum allowed AREF Voltage is 1.0V.

To make uncertainty as low as possible, a well-regulated external reference of 1.25V was used in this project. In this case, 1 LSB = 1250 mV/1023 = 1.22 mV. This means that when a DC voltage is measured, there is an uncertainty of $\pm$ 2 units, or $\pm$ 2.44 mV. Thus, if a N_0 number is associated with a voltage V_0, it will be reported as:

$$N = N_0 \pm 2 \tag{4.9}$$

5.2.2 Time Intervals

The micros() Arduino function can be used to measure time. It returns the number of microseconds since the microcontroller began running the current program. This number is always a multiple of 4 us which leads to an uncertainty δt of $\pm$ 2.0 us. A time interval can be measured as:

$$\Delta t = t_2 - t_1 \tag{4.10}$$

The associated uncertainty of the interval will be:

$$\delta \Delta t^2 = \delta t_1^2 + \delta t_2^2$$

$$\delta \Delta t \cong 3.0\, us$$

This means that when a time interval is measured, it will be reported as:

$$\Delta t = \Delta t_0 \pm 3.0\, us \tag{4.11}$$

4.2.3 Voltage Variation of a Ramp

As it was seen in Chapter 2, when a Capacitor with or without ESR is driven by a current source, the voltage will increase steadily with time, as a ramp. By measuring its slope K and Test Current Io, it is possible to determine the Capacitance using:

$$C = \frac{I_0}{K} \tag{4.12}$$

To determine K, the microprocessor must divide the variation in voltage by the variation in time, or:

$$K = \frac{\Delta V}{\Delta t} = \frac{V_2 - V_1}{t_2 - t_1} = \frac{V_{REF}}{2^N}\frac{(N_2 - N_1)}{t_2 - t_1} \tag{4.13}$$

Whereas DC Voltage is static and the total uncertainty is enough to completely describe the measurement, measuring the value of a voltage on a ramp may lead to additional errors beacause the voltage is changing during the acquisition process, as Figure 4.4 shows. Besides static total uncertainty there will also be a Dynamic Uncertainty given by:

$$D.U. = \frac{I_0}{C}.\Delta t_{ACQ} \tag{4.14}$$

Where I_0 is the current that is exciting the capacitor, C is the capacitance and Δt_{ACQ} is the Acquisition Time for the ADC. The standard analogRead() Arduino function has an acquisition time of 110 us. Through direct C language programming, it is possible to change the internal ADC clock pre-scaler and make conversions more quickly, typically in 13 us. This is the necessary code to do so:

```
#define cbi ( sfr , bit ) ( SFR BYTE( sfr ) &= ˜ BV( bit ) )
#define sbi ( sfr , bit ) ( SFR BYTE( sfr ) |= BV( bit ) )
void setup ()

{ sbi (ADCSRA, ADPS2) ;  cbi (ADCSRA, ADPS1) ;  cbi (ADCSRA, ADPS0) ;}
```

As the total static uncertainty is 2 LSB, if dynamic uncertainty is as low as 0.5 LSB, it will be negligible and static uncertainty can be used alone to completely describe the measurement. This means that the voltage on the ramp is changing, but the measurement is made so quickly that the voltage seems to be static. So, it is necessary to make sure that I_0 is chosen so that the D.U. is only 0.5LSB for the smallest capacitor to be measured.

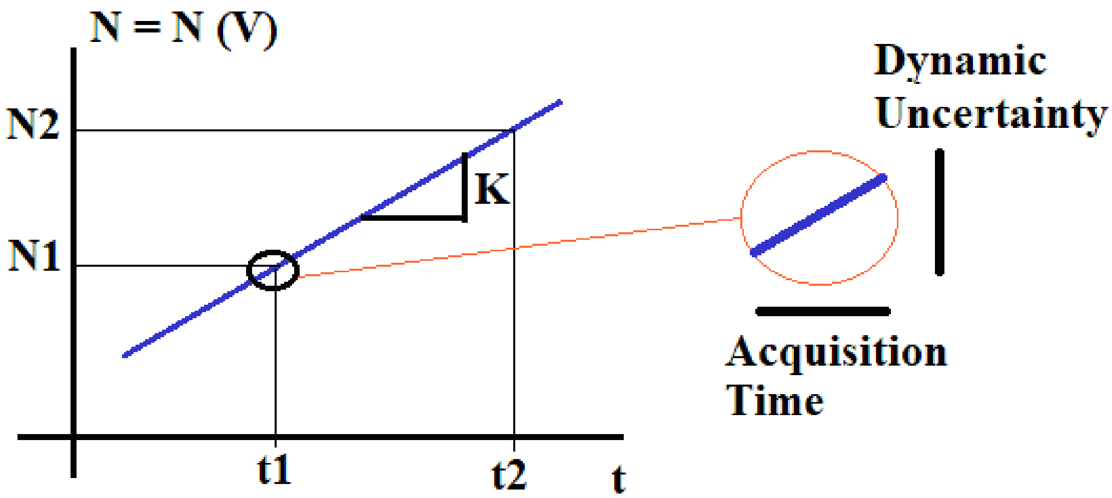

Figure 4.4 – Dynamic Uncertainty due to Acquisition Time on a voltage ramp

After some algebra and substitutions on equation 4.14:

$$I_0 = \frac{C_{min}}{\Delta t_{ACQ}} \frac{LSB}{2} \tag{4.15}$$

Electrolytic Capacitors starts typically at 1.0 μF. For a LSB of 1.22 mV, I_0 must be 50.0 μA. With just one scale, it will take 20 ms to measure a 1.0 uF unit but it will take too long to measure larger capacitors. So, besides a first scale ranging from 1.0 μF to 200.0 μF, there will be a second scale to measure bigger capacitances from 200.0 μF to 20.000 μF. In this case, the current test I_0 must be 5 mA.

Finally, with these Test Currents for these Capacitance ranges, N will have an uncertainty of 2 units and ΔN will have a slightly greater uncertainty of 3 units, that is:

$$\Delta N = \Delta N_0 \pm 3 \tag{4.16}$$

4.2.4 Capacitance

Figure 4.5a shows the simplified version of the circuit that is used to measure capacitance. The OA along with the bipolar transistor behave as a Current Source. Whereas a Voltage Reference of about 1250 mV is delivered to the Analog to Digital Converter (AREF), a fraction of this value of about 18% is used as DC REF – the Voltage Reference for the Current Source. The DC Ref is applied on the non-inverting input of the OA. Since the circuit has a negative feedback closed-loop, the same DC Ref appears on the non-inverting input. The current on R_0 will be DC REF/R_0. As the non-inverting input drains no current, the same current that flows through R_0 is obliged to flow through the Capacitor under test or the short relay, depending on if the relay is open or closed. The emitter of the transistor is connected to the input of one of the ADCs of the microcontroller (input A0). The ADC will measure the voltage on R_0 when the relay is closed or the voltage on R_0 along with the voltage on the Capacitor when the relay is open.

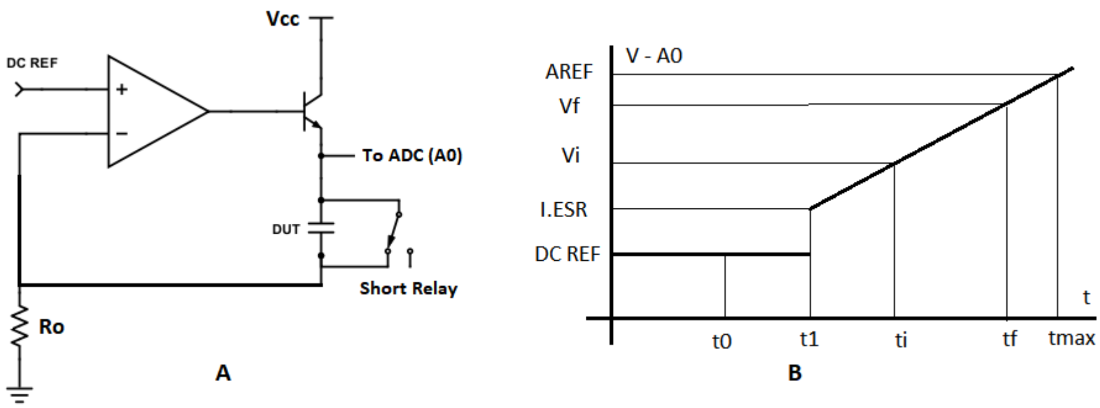

Figure 4.5 – Measuring Capacitance

Figure 4.5b shows the behavior of the voltage that is measured by A0. Firstly, the microprocessor measures DC REF with the relay closed and the number N_0 is associated with it. Then, at time t_0, the microprocessor orders the relay to open. Because of its mechanical delay, the relay opens at time t_1 and after that the voltage on the capacitor will increase linearly as it is driven by a constant current source. For the relay used in this project, the mechanical delay is about 3.0 ms. Thus, the first voltage measurement on the ramp must take place after this period to disregard the jump discontinuity due to ESR that happens at t_1. So, t_i is about 5 ms after t_0. At time t_i the microcontroller measures N_i (the number associated with V_i). When the A0 voltage reaches a value next to AREF, N_f (the number associated with V_f) is measured at time t_f.

Finally, as it was seen in chapter 2, the capacitance can be determined as:

$$C = \frac{I_0}{K} \tag{4.17}$$

In this equation, K is the slope of the voltage ramp. After some manipulations and using ΔN for $N_f - N_i$ and Δt for $t_f - t_i$, equation 4.17 becomes:

$$C = \frac{N_0}{R_0} . \frac{\Delta N}{\Delta t} \tag{4.18}$$

The uncertainty in the measurement can be calculated as:

$$\left(\frac{\delta C}{C}\right)^2 = \left(\frac{\delta N_0}{N_0}\right)^2 + \left(\frac{\delta R_0}{R_0}\right)^2 + \left(\frac{\delta \Delta N}{\Delta N}\right)^2 + \left(\frac{\delta \Delta t}{\Delta t}\right)^2 \tag{4.19}$$

The uncertainty in R_0 is constant and about 1.0% - the precision of the resistor used on the circuit. The uncertainty in N_0 is also constant: 2 units (uncertainty of the ADC) in 18% of AREF (184 units), that is roughly 1.0%. The uncertainty in ΔN is 3 units in roughly 80% of AREF (818 units), that is 0.4%. The uncertainty in Δt will be at most 3 us in 20 ms for the smallest capacitor that is measured which is negligible. Finally, the total uncertainty for the capacitance will be around 1.5%. The software will use Equation 4.18 to calculate the Capacitance and Equation 4.19 to calculate its uncertainty.

4.2.5 AC Voltages

To measure the ESR of the DUT, the peak values of AC sinusoidal signals must be measured. Instead of using analog circuitry to convert the AC signal into a DC value, a statistical approach was chosen instead. The AC signal with amplitude A to be measured is delivered to the input of the ADC via a coupling capacitor with negligible capacitive reactance at the frequency of operation. A voltage divider with equal resistors delivers half the Voltage Reference of the ADC to the input, as Figure 4.6 shows. There will be an AC signal superposed on a DC level on the input, making the voltage fluctuate from AREF/2 – A to AREF/2 + A

Normally, the ADC can measure the instantaneous voltage of this signal by calling the usual analogRead() function. If this function is called many times and the values are stored in an array, many instantaneous values are stored. If the number of measurements is very large, it is highly likely that the maximum and minimum values of the AC signal superposed on the DC level are recorded. Thus, the maximum and minimum values stored in the array (N_{max} and N_{min}) will give us the numbers that correspond to AREF/2 + A and AREF/2 – A as long as the number of measurements is high enough. Furthermore, as the number of interactions increases, the uncertainty gets lower and lower, eventually approaching the usual DC measurement uncertainty of 2 LSB for voltages and 3LSB for voltage variations. Tests showed that this happens for roughly over 10000 interactions.

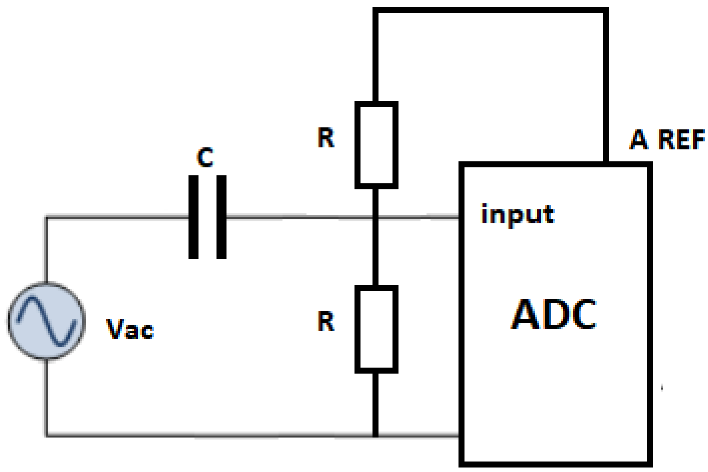

Figure 4.6 – ADC measuring AC Voltages

Finally, in order to get the ADC number that corresponds to the Amplitude A:

$$A = \frac{N_{max} - N_{min}}{2} \tag{4.20}$$

The amplitude of the signal can be reported as:

$$A = A_0 \pm 2 \tag{4.21}$$

4.2.6 Frequency

A third-party library was used to determine the frequency of the AC signal that is used in the project. The library called FreqCount was written by Paul Stoffregen and is available at www.arduinolibraries.info/libraries/freq-count. The AC signal is converted into a digital square signal by a bipolar transistor and then delivered to input D5 of the microprocessor. The library measures the frequency by employing the freqCount.read() function. The uncertainty claimed is in the order of units of Hertz which turned out to be true after some tests using a precision frequency meter. Thus, the frequency determined by this method can be reported as:

$$f = f_0 \pm 1 \tag{4.22}$$

4.2.7 ESR

As it was seen in Chapter 2, ESR can be measured using an AC voltage divider. An AC signal is applied to the DUT in series with a known resistor R_0 and an output signal is collected on R_0 as it was shown in Figure 4.7. Then, the amplitude of the input and output voltages are measured, giving numbers N_{in} and N_{out}. When the reactance X_c is much smaller than R_0 as it happens on the second scale of the Analyzer, the ESR can be determined by:

$$ESR = \left(\frac{N_{in}}{N_{out}} - 1\right) R_0 \tag{4.23}$$

However, if X_c is not small enough, as on the first scale that measures small capacitances, the reactance must be taken into account, and the ESR must be determined by:

$$ESR = \sqrt{\left(\frac{N_{in}}{N_{out}}\right)^2 R_0^2 - X_c^2} - R_0 \tag{4.24}$$

The software will use these equations to calculate the Capacitance of the DUT.

Differently from the uncertainty on the Capacitance that is roughly constant and easy to be calculated anyway, the ESR uncertainty is variable and depends on many quantities in a more complicated mathematical relationship. Before deriving the complete expressions for these uncertainties, it is important to understand how uncertainty behaves when some appropriate simplifications are done.

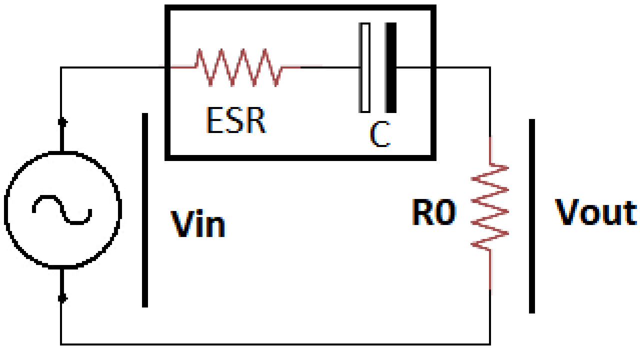

Figure 4.7 – Measuring ESR

Consider Equation 4.23, used for higher capacitances, which has a simpler form. The precision resistor R_0 is constant. It has 10.0 Ω and uncertainty of 1.0%. This value was the smallest value that could be used that did not bring about perceivable distortion on the sinusoid signal. The input voltage N_{in} is approximately constant. Its value is 1000 to take advantage of all ADC range and its uncertainty is about 2 LSB or 0.2%. Whereas R_0 and N_{in} are constant and will have small and constant uncertainties, N_{out} can range from 1 to 1000 and, although its absolute uncertainty is only 2 LSB, the relative uncertainty will be variable throughout the scale and in some situations it will be much higher than 1.0%. Thus, analyzing how uncertainty on ESR depends on N_{out} for R_0 and N_{in} remaining constant can provide a satisfactory idea of how total uncertainty behaves.

Next, Equation 4.25 is Equation 4.23 with $N_{in} = 1000$ and $R_0 = 10$ ($N_{out} = N$):

$$ESR = \frac{10000}{N} - 10 \qquad (4.25)$$

This will lead to a relative uncertainty on ESR of:

$$\frac{\delta ESR}{ESR} = \frac{\frac{20000}{N^2}}{\frac{10000}{N} - 10} \tag{4.26}$$

When N is too low, the relative uncertainty gets too high, even more than 100%. This is not a big issue since so high ESR values are not common. As N increases, the uncertainty decreases. When ESR is 100 ohms, its uncertainty is very low, roughly 2.5%. For bigger N and smaller ESR, the uncertainty gets approximately constant, reaching values as low as 0.8% when ESR is in the order of 7.0 ohms. But when ESR gets too low, its uncertainty starts to increase again, reaching 2.0% at 1.2 ohms. At 0.2 ohms, the uncertainty is about 10%, much greater than the uncertainty on R_0. At ESR = 0.1 ohm, the uncertainty is already 20% and this point was chosen as the minimum value that the system can measure and deliver a dependable result. Figure 4.8 shows how ESR depends upon N, for values below 100 ohms. Figure 4.9 shows how the relative uncertainty of ESR depends upon N. Extreme values were removed for better visualization.

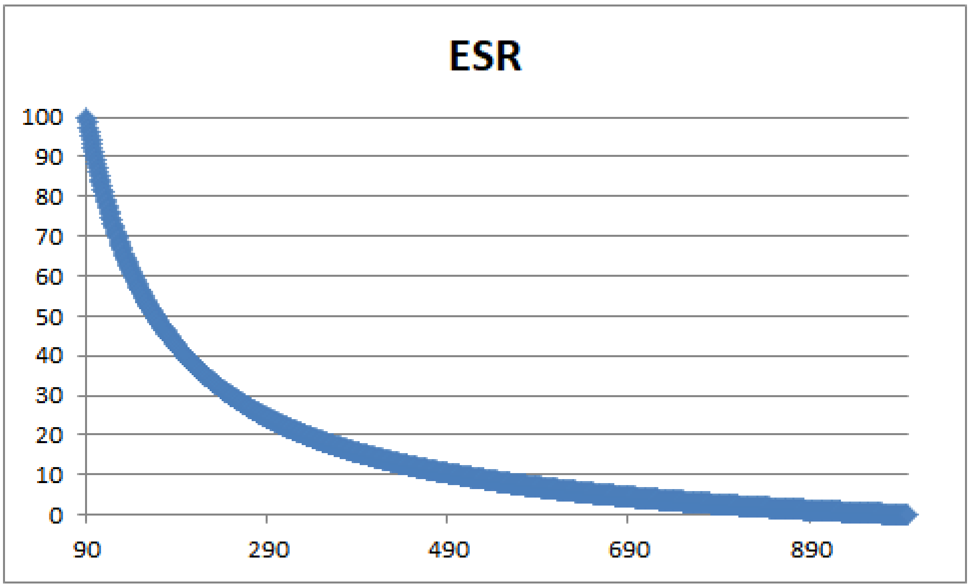

Figure 4.8 – ESR versus N

Finally, equation 4.27 is the exact expression to calculate uncertainty when ESR is calculated with Equation 4.23:

$$\delta ESR^2 = \frac{400}{{N_{out}}^2} + \frac{400{N^2}_{in}}{N_{out}^4} + 0.01(\frac{N_{in}}{N_{out}} - 1)^2 \tag{4.27}$$

For the case of Equation 4.24, firstly it is necessary to find the uncertainty in X_c. This can be done using:

$$\left(\frac{\delta X_c}{X_c}\right)^2 = \left(\frac{\delta f}{f}\right)^2 + \left(\frac{\delta C}{C}\right)^2 \tag{4.28}$$

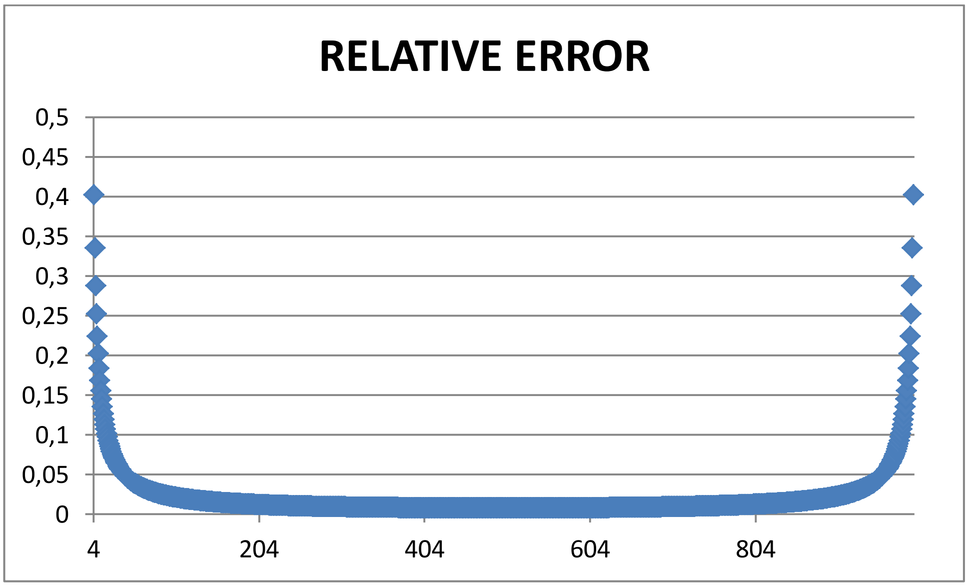

Figure 4.9 – Uncertainty on ERS versus N

The frequency of operation was fixed around 10.0 kHz. This value presented good performance as far as stability and distortion are concerned. The uncertainty on frequency (units of hertz on typically 10 kHz – 0.01%) is negligible when compared to 1.5% for Capacitance. Thus, uncertainty of capacitive reactance is also 1.5%.

Eventually, after some algebra, uncertainty for Equation 5.24 will be:

$$\delta ESR^2 = \frac{\frac{40000N_{in}^2}{N_{out}^4}}{\Delta} + \frac{\frac{40000N_{in}^4}{N_{out}^6}}{\Delta} + \frac{2.25 \cdot 10^{-4} \cdot X_C^4}{\Delta} + 0.01(\frac{\frac{10N_{in}^2}{N_{out}^2}}{\Delta} - 1) \tag{4.29}$$

Where:

$$\Delta = \left(\frac{N_{in}}{N_{out}}\right)^2 R_0^2 - X_c^2 \tag{4.30}$$

Chapter 5
Capacitor Analyzer – Hardware and Software

5.1 Hardware

Figure 5.1 shows the primary power supply for the Capacitor Analyzer. It is a classical linear power supply. It comprises a 12+12V 500mA power transformer, a full bridge rectifier, filter capacitors and linear voltage regulators that provides + 12V and -12V for the operational amplifiers and +5V for the microprocessor circuits.

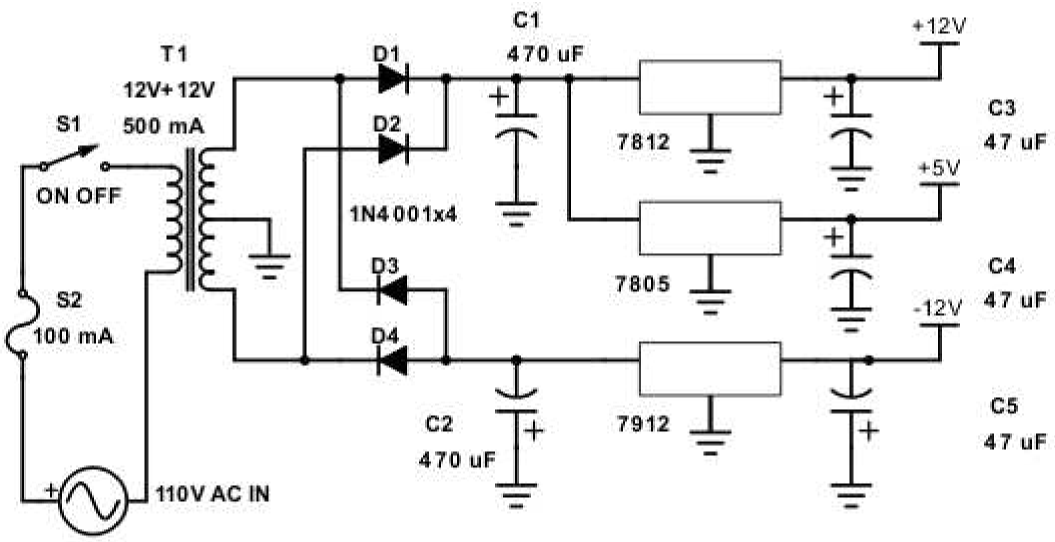

Figure 5.1 – Primary Power Supply

Figure 5.2 shows the Reference Voltage Section. It uses all the four operational amplifiers inside one LM324. The LM385 is a precision voltage reference that delivers a stable 2.5V primary reference. Its bias current was chosen to be about 1.0 mA to make it work properly, according to its datasheet. This voltage is buffered by an OA and divided by two by means of a voltage divider and becomes about 1250 mV. This value is also buffered by another AO and delivered to the ADC Voltage Reference (AREF). After another buffer, another voltage divider reduces the 1250 mV to 18% of this value, typically 225 mV that will be used as a Voltage Reference for the Current Source (DC REF). Finally, after another buffer, half of the AREF value is produced by a voltage divider and delivered to the Analog Inputs A1 and A2 working as Offset References for AC measurements.

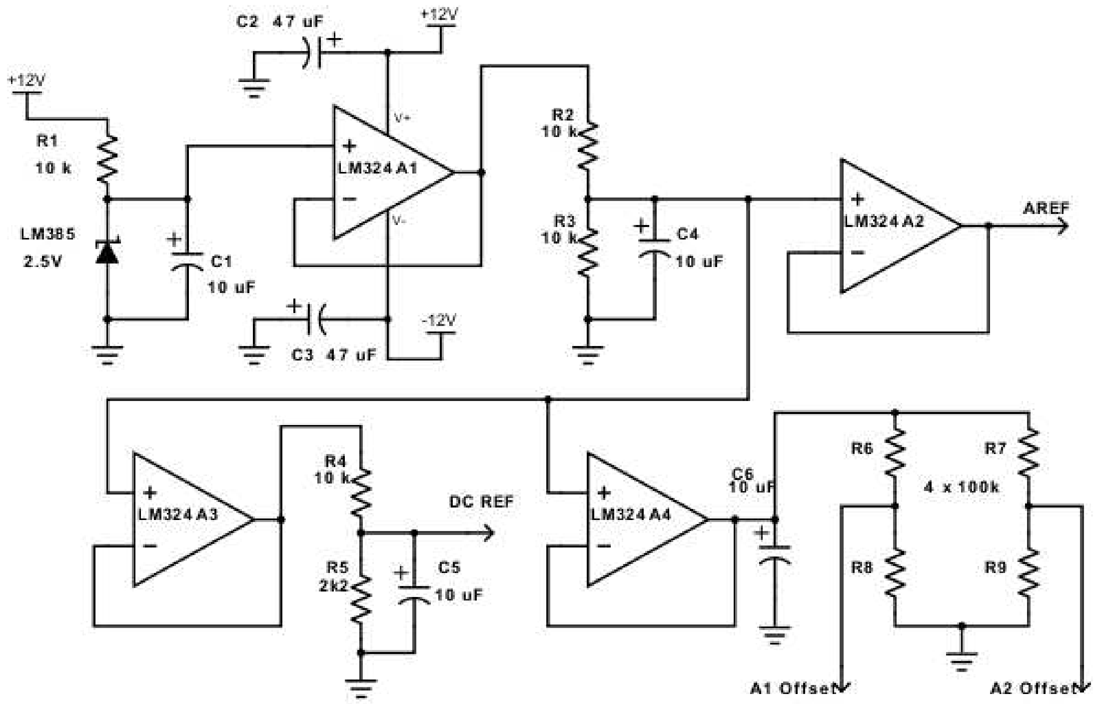

Figure 5.2 – Reference Voltage Section

Figure 5.3 shows the AC Signal Generator. In this section, another LM324 is used. The first unit works as a phase shift oscillator. It consists of an inverting amplifier and a passive network of 3 equal Resistors and 3 equal Capacitors. The network provides a phase shift of 180° at a specific frequency f_0. The amplifier will add another 180° and the positive feedback will occur, making the circuit oscillate as long as the gain of the amplifier is sufficiently high to compensate for the attenuation of the passive network. With the values that were chosen, it produces a signal of approximately 10.0 kHz with very low distortion.

The sinusoidal signal is removed from the inverting input and buffered by another OA. A 100 k ohms trim pot can adjust the amplitude of the signal that will be delivered to the output power amplifier. The ideal adjustment is about 1200 mV so that all the ADC compliance is used reaching the best precision.

The third OA along with power complementary transistors BD139 and BD140 work as a Push-Pull power amplifier, being able to deliver the sinusoidal signal to low impedance loads without appreciable losses and distortion.

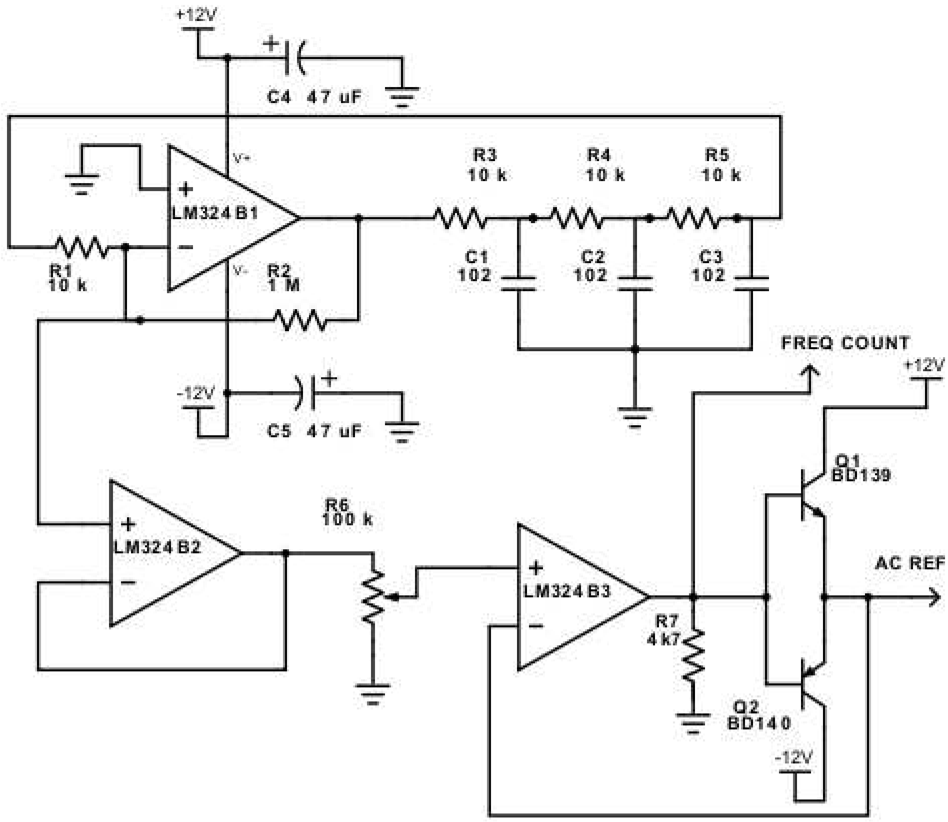

Figure 5.3 – AC Signal Generator

Figure 5.4 shows the measurement section. The OA and the bipolar transistor work as a Current Source. When Relay A is open, the current is obliged to flow through the DUT. While it is closed, the DUT gets discharged completely. Relay B has the purpose of connecting the DUT either to the Current Source to measure Capacitance or to the AC Voltage Divider to measure ESR. Relay C changes the precision resistors that determine the Current for the Current Source. These resistors establish a current of roughly 50 μA and 5.0 mA for each capacitance scale. Microprocessor Input A0 measures the voltage developed on the DUT when excited by the current source whereas inputs A1 and A2 measure the AC voltage developed on the voltage divider for ESR measurement.

Figure 5.5 shows the Relay Control Section. It comprises three drivers for each of the three Relays of the circuit. Each driver has a bipolar transistor that switches the coils of each relay. Diodes for protection were included. Microprocessor digital outputs D11, D10 and D9 switch Relays A, C and B respectively.

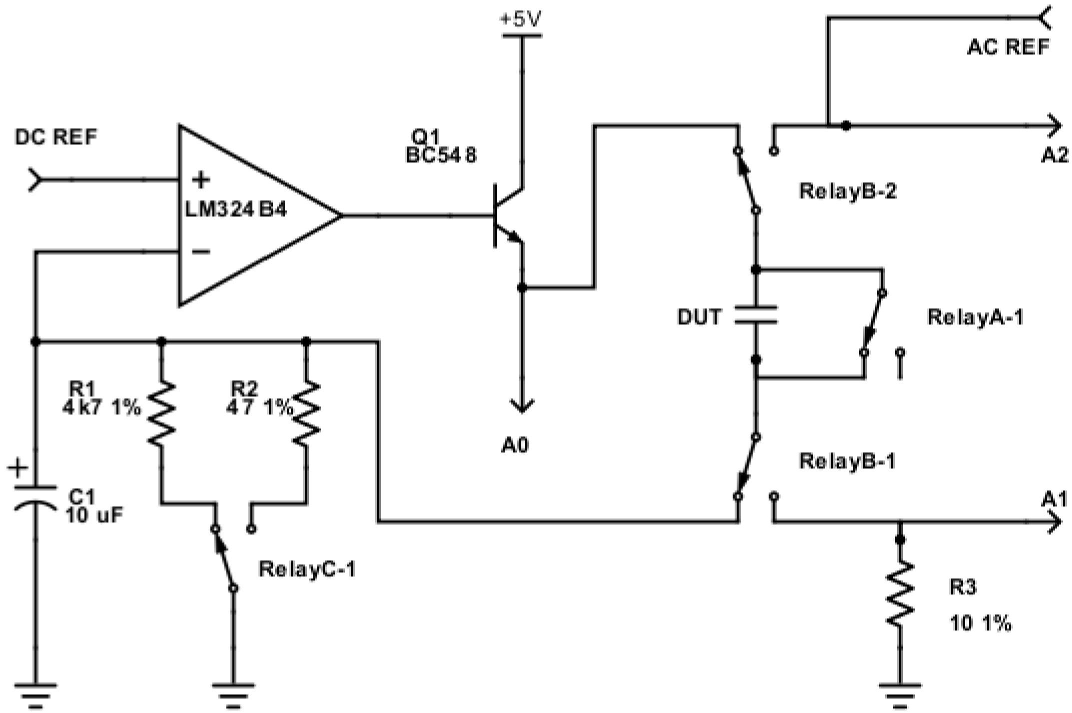

Fig 5.4 – Measurement Section

Figure 5.6 shows the Display Section. It is a standard circuit for a 16x2 display. It requires 4 data lines (D7, D6, D5 and D4) and two control lines (EN and RS). These six lines are connected to the six outputs of the Microcontroller that are used for display communication (D2, D3, D4, D6, D7 and D8). The supply voltage for the module is 5.0V. Resistors R1 and R2 provide a good contrast level for the characters.

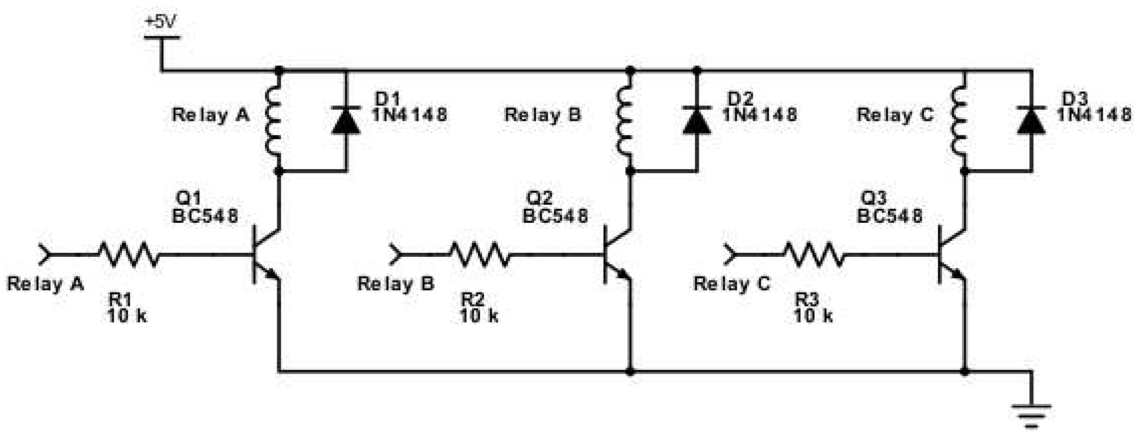

Fig 5.5 – Relay Control Section

Eventually, Figure 5.7 shows the Microcontroller section. The power supply of 5.0V is delivered to the Vcc pins. The GND pins are connected to the ground. The 16 MHz oscillator crystal is connected to pins XTAL1 and XTAL2. The AREF pin receives the reference voltage for the ADC.

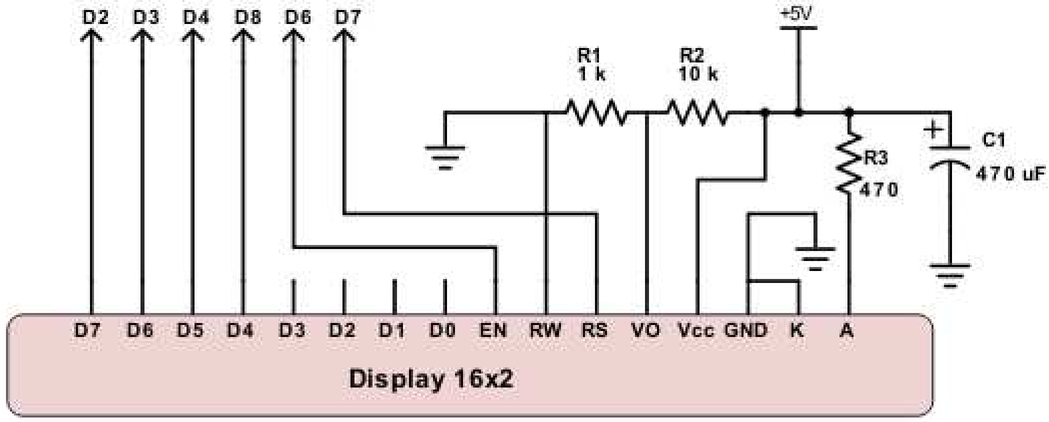

Figure 5.6 – Display Section

The programming lines are RS, RX, TX and GND. Through these lines, the software is uploaded to the unit. The communication with the display is done by means of pins D2, D3, D4, D6, D7 and D8. Input D5 is used to measure the frequency of the AC generator. Outputs D9, D10 and D11 are used to switch the Relays. Input D13 is used to switch the software to Configuration Mode.

Finally, analog input A0 measures the DC voltage developed on the DUT when it is driven by the current source. Analog Inputs A1 and A2 are responsible for measuring peak AC voltage on the voltage divider used to determine ESR. The AC signal is coupled via 470 nF capacitors. A DC Offset voltage of AREF/2 is also delivered to theses inputs.

5.2 Software

The software starts importing the library for the display and initializing its respective object. The library to measure frequency and the functions to speed up the ACD acquisition are also included.

```
#include <LiquidCrystal.h>
const int rs = 7, en = 6, d4 = 8, d5 = 4, d6 = 3, d7 = 2;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);
#include <FreqCount.h>
#define cbi(sfr,bit) (_SFR_BYTE(sfr) &= ~_BV(bit))
#define sbi(sfr,bit) (_SFR_BYTE(sfr) |= _BV(bit))
```

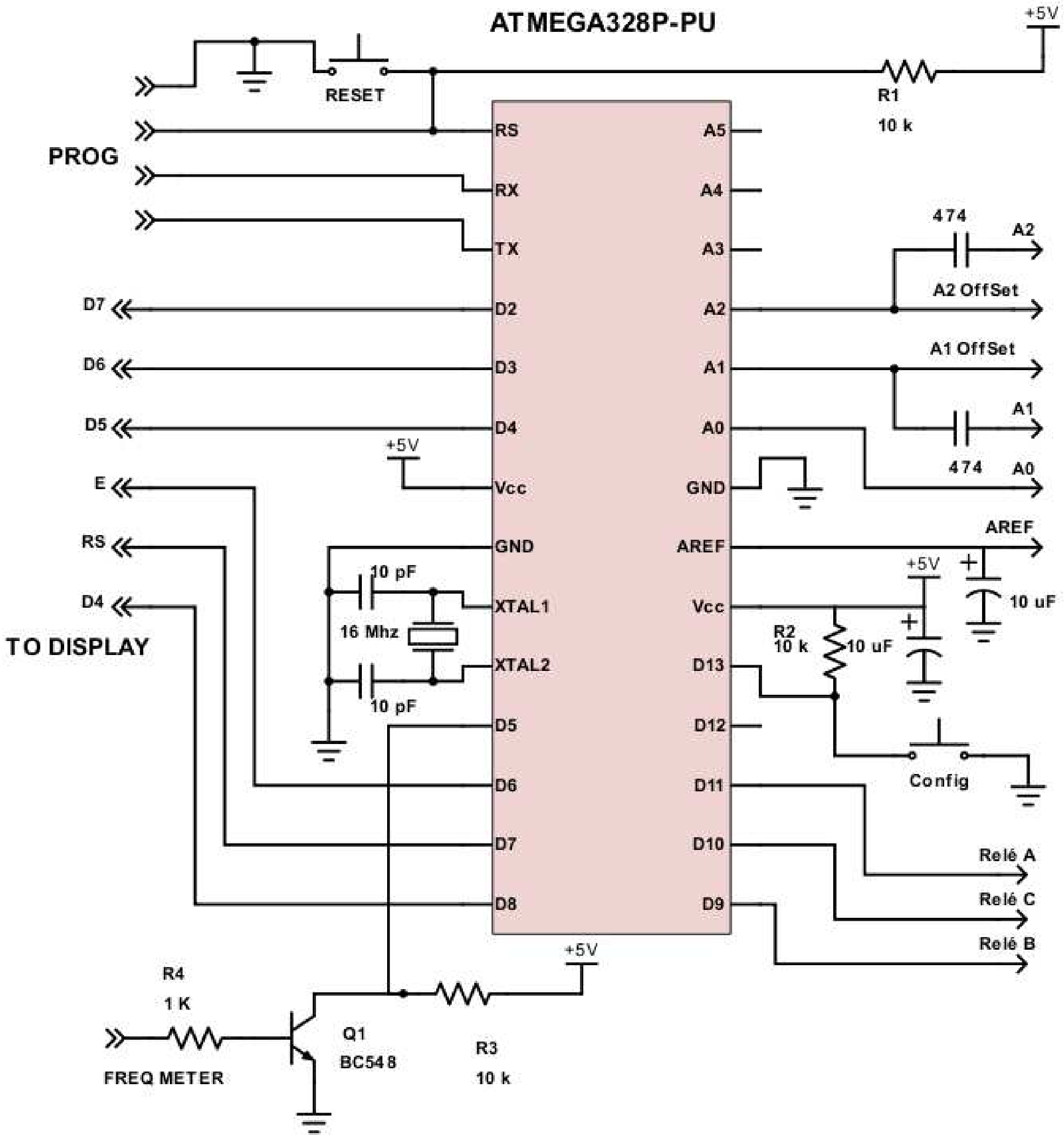

Figure 5.7 – Microcontroller Section

The set up() function establishes the analog Reference for the ADC as being external, gives a welcome message via display, and configures the outputs that will control the relays and configures the input that will check if the instrument is in the calibration mode, as well as turn all relays off.

```
void setup() {
analogReference(EXTERNAL);
sbi(ADCSRA, ADPS2); cbi(ADCSRA, ADPS1); cbi(ADCSRA, ADPS0);
lcd.begin(16, 2);  lcd.print("Cap Analyser");
lcd.setCursor(0, 1); lcd.print("Initializing...");
delay(3000);
pinMode(9, OUTPUT);    // mode LOW: Capacitance          HIGH: Impedance
pinMode(10, OUTPUT);   // scale LOW: low current          HIGH: high current
pinMode(11, OUTPUT); //short-ciruit LOW: short-circuit   HIGH: cap available
pinMode(13, INPUT);    // Calibration
digitalWrite(9, LOW); digitalWrite(10, LOW); digitalWrite(11, LOW);}
```

Then, the loop () function starts with the definition of the some global variables that will be used in the program.

```
int Tdead = 5000;          double R0 = 4700;            double R1 = 47;
double Ccontrol = 200;     double Coverflow = 1000;     double Tover=0;
double Tcontrol = 0;       double DC = 0;               double C = 0;
double REF = 0;            long j = 0;                  long Verify = 0;
long TF = 0;               long T0 = 0;                 int NF = 0;
int N0 = 0;                int count = 0;
```

After that, there is a calibration routine that is triggered when the user removes a jumper on the D13 input. It measures the peak-to-peak voltage of the AC generator. The gain trim-pot must be adjusted so that the reading approaches 1000. At 1023, the signal will be saturated and less than 1000 will limit the ADC compliance.

```
CAL:
if (digitalRead(13)) { lcd.clear(); lcd.print("CALIBRATION");
lcd.setCursor(0, 1); lcd.print("Adj for apx 1000");
delay(2000); digitalWrite(11, HIGH); digitalWrite(9, HIGH); delay(200);
```

```
int MINIMUM = 1023; int MAXIMUM = 0;
for (int G = 0; G < 10000; G++) {int A = analogRead(2);
if (A > MAXIMUM) { MAXIMUM = A;}
if (A < MINIMUM) { MINIMUM = A;}}
int VT = MAXIMUM - MINIMUM; delay(200);
digitalWrite(11, LOW); digitalWrite(9, LOW);
lcd.clear(); lcd.setCursor(0, 1); lcd.print(VT); delay(3000); goto CAL;}
```

Then, a message asking to insert a Capacitor is displayed. The Reference Voltage VREF is measured. The DUT short-circuit is turned off and the software wait for 5.0 ms (Tdead) to start measuring the voltage on the DUT. The first voltage and time N0 and T0 are measured. If N0 is greater than 1000, this means that no capacitor is connected and the software returns to the beginning. Otherwise, it keeps measuring and gets NF and TF. If it takes too long, the software switches to the second scale. The capacitance C and its percentage uncertainty DC is finally calculated.

```
lcd.clear(); lcd.print("Insert a Cap..."); delay(10000);
ESCALA1:
j = 0;
for (int i = 0; i < 100; i++)
{ j = j + analogRead(0);}
REF = (float) (j) / 100; Tcontrol = 650 * Ccontrol; delay (500);
digitalWrite(11, HIGH); delayMicroseconds(Tdead);
N0 = analogRead(0); T0 = micros();
if (N0 > 1000) { digitalWrite(11, LOW); goto START; }
lcd.clear(); lcd.print("Measuring Cap");
lcd.setCursor(0, 1); lcd.print("Scale 1 - Wait...");
Verify = 0;
while (analogRead(0) < (N0 + 30))
{Verify = micros() - T0;
 if (Verify > Tcontrol) {goto ESCALA2;}}
while (analogRead(0) < 950) {}
NF = analogRead(0); TF = micros();digitalWrite(11, LOW);
C = ((TF - T0) * REF) / ((NF - N0) * R0);
```

```
DC = pow(2.00/REF,2)+pow(0.01,2) + pow(3/(NF-N0),2);
DC = 100*pow(DC,0.5);
lcd.clear(); lcd.print("Cap Measured!");
delay(1000); goto IMPEDANCE;
```

The second scale is much similar to the first scale. The only difference is that the Relay C is ON, changing the test current form 50 μA to 5.0 mA.

```
ESCALA2:
digitalWrite(11, LOW); lcd.clear();  lcd.print("Cap too high!");
lcd.setCursor(0, 1); lcd.print("going to Scale 2");  delay(3000);
digitalWrite(10, HIGH); delay(500);
j = 0;
for (int i = 0; i < 100; i++)  { j = j + analogRead(0);}
REF = (float) (j) / 100;Tover = 650 * Coverflow;
digitalWrite(11, HIGH); delayMicroseconds(Tdead);
N0 = analogRead(0); T0 = micros();
lcd.clear(); lcd.print("Measuring Cap - 2");
lcd.setCursor(0, 1); lcd.print("Scale 2 - Wait...");
Verify = 0;
while (analogRead(0) < (N0 + 30))
{ Verify = micros() - T0;
if (Verify > Tover) {goto ESCALA3;}}
while (analogRead(0) < 950) { }
NF = analogRead(0); TF = micros();
digitalWrite(11, LOW); digitalWrite(10, LOW);
C = ((TF - T0) * REF) / ((NF - N0) * R1);
DC = pow(2.00/REF,2)+pow(0.01,2) + pow(3/(NF-N0),2);
DC = 100*pow(DC,0.5);
lcd.clear(); lcd.print("Cap Measured!");
delay(1000); goto IMPEDANCE;
```

If the Capacitor is too high, the software goes to overflow scale.

```
ESCALA3:
digitalWrite(11, LOW);digitalWrite(10, LOW);
lcd.clear();lcd.print("Cap Overflow...");
lcd.setCursor(0, 1);lcd.print("...");
C = 2000000; delay (2000);
```

After measuring capacitance, the software begins the IMPEDANCE measurements. The first step is to determine the frequency of the oscillator and the capacitive reactance:

```
IMPEDANCE:
lcd.clear(); lcd.print("Impedance Meter");
lcd.setCursor(0, 1);lcd.print("Wait...");
FreqCount.begin(1000); delay(1500);
if (FreqCount.available()) {count  = FreqCount.read();
FreqCount.end();
double Freq = (double) count;
double XC = 1.00 / (2 * 3.14 * Freq * C * 0.000001);
```

After that, the resistance of the wires is determined. This is done leaving the DUT short-circuited. This resistance, called r, will be subtracted from the ESR at the end:

```
digitalWrite(11, LOW); digitalWrite(9, HIGH); delay(1000);
int MINIMU = 1023; int MAXIMU = 0;
for (int G = 0; G < 10000; G++) { int A0 = analogRead(1);
if (A0 > MAXIMU) {MAXIMU = A0;}
if (A0 < MINIMU) {MINIMU = A0;}}
int vr = (MAXIMU - MINIMU)/2;
int  MINIMUU = 1023;int  MAXIMUU = 0;
for (int G = 0; G < 10000; G++) {int AA0 = analogRead(2);
if (AA0 > MAXIMUU) {MAXIMUU = AA0;}
if (AA0 < MINIMUU) { MINIMUU = AA0;} }
int vt = (MAXIMUU - MINIMUU)/2;
```

```
digitalWrite(11, LOW);digitalWrite(9, LOW);
double f = ((double) vt) / ((double) vr);
double r = (f - 1.00) * 10.0;
```

After that, a similar routine is carried out to calculate the ESR and its uncertainty. During this process, the DUT is not short-circuited.

```
digitalWrite(11, HIGH); digitalWrite(9, HIGH); delay(1000);
int MINIMUM = 1023; int MAXIMUM = 0;
for (int G = 0; G < 10000; G++) {int A = analogRead(1);
if (A > MAXIMUM) {MAXIMUM = A;}
if (A < MINIMUM) { MINIMUM = A; } }
int VR =(MAXIMUM - MINIMUM)/2;
int  MINIMUMM = 1023;int  MAXIMUMM = 0;
for (int G = 0; G < 10000; G++) {int AA = analogRead(2);
if (AA > MAXIMUMM) {MAXIMUMM = AA;}
if (AA < MINIMUMM) {MINIMUMM = AA; }}
int VT = (MAXIMUMM - MINIMUMM)/2;
digitalWrite(11, LOW);digitalWrite(9, LOW);
double F = ((double) VT) / ((double) VR);
double ESR;double DESR = 0;
if (XC >= 0.1) {double DELTA = (100.00 * F * F) - (XC * XC);
ESR = sqrt (DELTA) - 10.0 - r;
DESR=(40000*pow(VT,2))/(DELTA*pow(VR,4))+
(40000*pow(VT,4))/(DELTA*pow(VR,6)) + ((0.000225*pow(XC,4))/DELTA) +
0.01*((10*pow(VT,2))/(DELTA*pow(VR,2))-1);
 DESR = pow(DESR,0.5);DESR = (DESR/ESR)*100;}
else{ESR = (F - 1.00) * 10.0 - r;
DESR = (400/pow(VR,2))+(400*pow(VT,2)/pow(VR,4))+(0.01*pow(F-1,2));
DESR = pow(DESR,0.5);DESR = (DESR/ESR)*100;}
if (ESR < 0) {ESR = 0.00;}
```

Eventually, the capacitance value is formatted and all the results are displayed.

```
if (C < 10.0) {C = C;}
else if (C >= 10.0 && C < 100.0) {C = 10 * C;C = round (C);C = C / 10;}
else if (C >= 100.0 && C < 1000.0) {C = round(C);}
else if (C >= 1000.0 && C < 10000) { C = C / 10;C = round (C); C = C * 10;}
else if (C >= 10000 && C < 100000) {C = C / 100;C = round (C);C = C * 100;}
else if (C >= 100000) { C = C / 1000;C = round (C);C = C * 1000;}
if (C == 2000000) {
lcd.clear();lcd.print("Cap Overflow");lcd.setCursor(0, 1);  lcd.print("ESR = ");
lcd.print(ESR);lcd.print(" ohm");}
else {if (C <= 1000) {lcd.clear();lcd.print("Cap = ");lcd.print(C); lcd.print(" uF");
lcd.setCursor(0, 1);lcd.print("ESR = ");lcd.print(ESR);lcd.print(" ohm");
else {double CC = C/1000;lcd.clear(); lcd.print("Cap = "); lcd.print(CC);
lcd.print(" mF");lcd.setCursor(0, 1);lcd.print("ESR = ");lcd.print(ESR);
lcd.print(" ohm");} }
delay(10000);
lcd.clear(); lcd.print("DCAP = ");lcd.print(DC); lcd.print(" %");
lcd.setCursor(0, 1);  lcd.print("DESR = "); lcd.print(DESR);
lcd.print(" %");
delay(10000);}
```

Chapter 6

Capacitor Analyzer – Construction, Tests, Validation and Conclusions

6.1 Construction

The printed circuit board of the equipment was designed by using Fritzing software, available at fritzing.org. Figure 6.1 shows the final layout of the PCB.

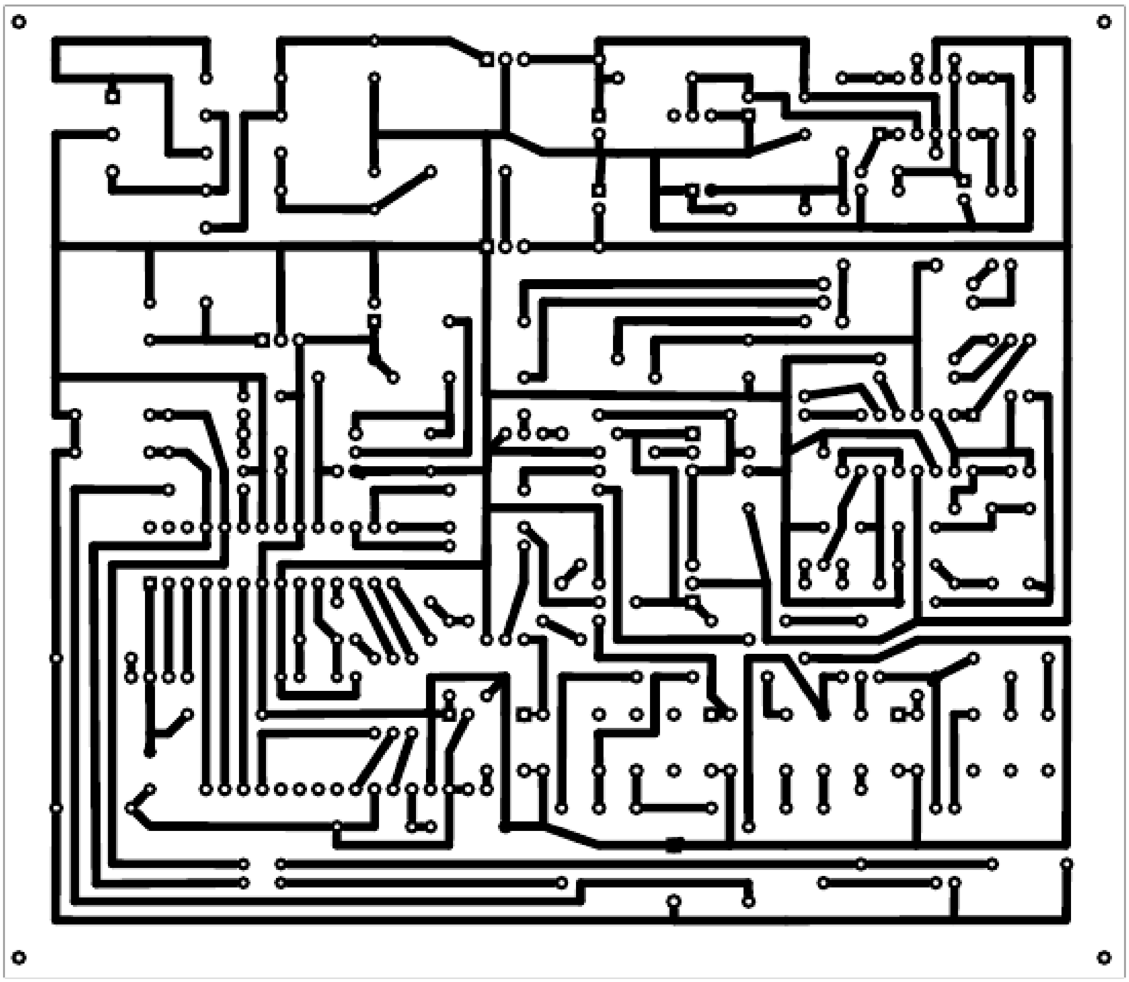

Figure 6.1 – Capacitor Analyzer PCB

Figure 6.2 shows the inside view of the Equipment, after completely assembled.

Figure 6.3 shows the appearance of the front panel, showing the results of measurement of a 22.0 μF test Capacitor.

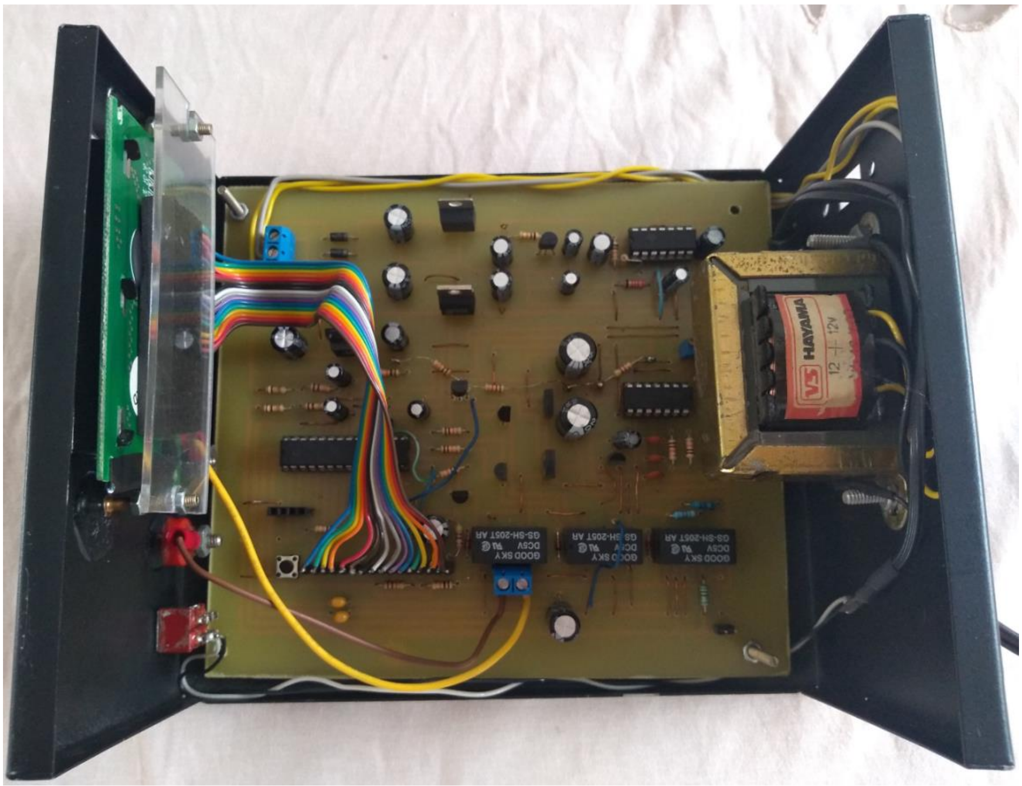

Figure 6.2 – Inside view of the Equipment

6.2 Tests and Validation

After verifying that the Equipment is working properly by testing all of its sections, it is time to test its performance.

The first test was carried out by selecting some brand new EPCOS commercial electrolytic capacitors and measuring its Capacitance and ESR – C_0 and ESR_0. The values were selected in order to virtually cover the entire range of electrolytic capacitors. The measured capacitance must approach its nominal value C. After that, a 1.0 ohm resistor R_0 with 1.0% precision is connected in series with the capacitor and the Capacitance and ESR of the association (C_F and ESR_F) are measured. If the equipment is working properly and is able to measure C and ESR independently as it was claimed, C_F and C_0 must be equal and ESR_F must be equal to ESR_0 + 1.0 ohm.

Table 6.1 shows all the results. Capacitances are in μF and resistances are in ohms. C_T and ESR_T are the theoretically expected values for C_F and ESR_F and ΔC and ΔESR are the percentage deviations from the expected.

C	C_0	C_T	C_F	ESR_0	ESR_T	ESR_F	ΔC	ΔESR
4.7	4.62	4.62	4.61	0.76	1.76	1.77	-0.21	0.56
10.0	9.94	9.94	9.92	3.65	4.65	4.67	-0.20	0.43
100.0	98.40	98.40	98.40	1.81	2.81	2.85	0.00	1.42
470.0	461.0	461.0	461.0	0.44	1.44	1.42	0.00	-1.38
1000.0	985.0	985.0	982.0	0.32	1.32	1.33	-0.30	0.75

Table 6.1 – Results of the first Test

The measured values for the association are under the expected values. The maximum deviation was less than 0.5% for capacitance and less than 1.5% for ESR.

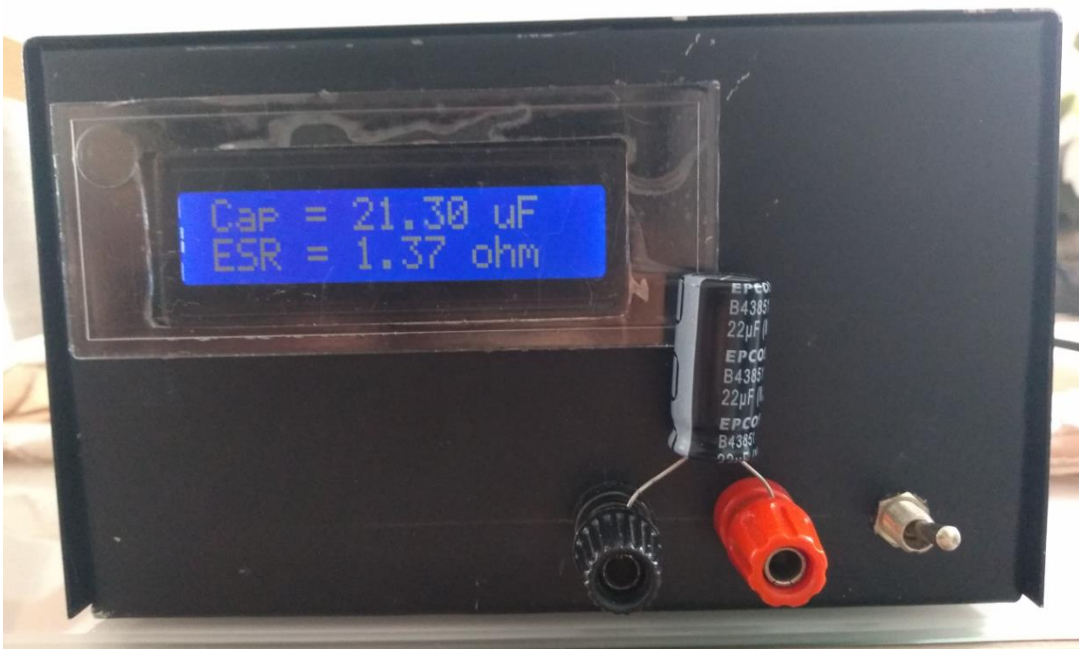

Figure 6.3 – Capacitor Analyzer front panel

The second test involves five sets of two EPCOS capacitors of nominal capacitance C_1 and C_2. The Capacitance and ESR of each capacitor are measured with the Analyzer. These values are displayed in Table 6.2.

After that, the capacitors C_1 and C_2 are connected in series and the Capacitance and ESR of the association are measured (C_{12M} and ESR_{12M}). Again, if the equipment is working properly and is able to measure C and ESR independently as it was claimed, the expected value for C_{12M} is $C_{1M}.C_{2M}/C_{1M} + C_{2M}$ and for ESR is $ESR_{1M} + ESR_{2M}$. The theoretically expected values are denoted by C_T and ESR_T and the deviations from the expected are denoted by ΔC and ΔESR. Table 6.3 shows the results for the second Test.

C_1	C_{1M}	ESR_{1M}	C_2	C_{2M}	ESR_{2M}
4.7	4.4	1.23	10.0	9.8	1.44
47.0	44.5	0.77	100.0	102.0	0.93
100.0	98.3	1.02	220.0	215.3	0.47
470.0	453.0	0.32	1000.0	992.0	0.21
4700.0	4530.0	0.12	3300.0	3220.0	0.17

Table 6.2 – Individual Values for Capacitors used on the Second Test

Again, the results are under the expected values. The maximum deviation was less than 1.5% for capacitance and less than 2.0% for ESR.

C_{12M}	C_{12T}	ΔC	ESR_{12M}	ESR_{12T}	ΔESR
3.01	3.04	-0.98	2.65	2.67	-0.75
30.6	31.0	-1.29	1.71	1.70	0.58
68.1	67.5	0.88	1.52	1.49	1.97
315.0	311.0	1.26	0.54	0.53	1.88
1860	1880.0	-1.06	0.29	0.29	0.00

Table 6.3 – Results of the second Test

The final and most important test involves the direct comparison of the measurements obtained by the Capacitor analyzer and a GCD Analyzer. A BioLogic SP-200 Potentiostat (see figure 6.4) was used to perform Galvanostatic Charge Discharge Analysis in a set of eight capacitors of different values and brands. Their capacitances and ESR were calculated as described in section 2.5. The test current was fixed at 200 μA and the potential window was 5.0V.

Figure 6.4 – BioLogic SP-200 Potentiostat

After that, each capacitor was connected to the Capacitor Analyzer and its capacitance and ESR were measured as well as the uncertainties. Table 6.4 shows the nominal capacitance C of each component, its brand, capacitance and ESR measured by GCD (C_{gcd} and ESR_{gcd}) and also capacitance, ESR and uncertainties measured by the Capacitor Analyzer (C_0, ESR_0, δC, δESR).

C	Brand	C_{gcd}	ESR_{gcd}	C_0	ESR_0	δC	δESR
1.0	Epcos	1.02	5.12	1.01	5.15	1.5%	2.2%
4.7	Ketuo	4.62	3.77	4.60	3.75	1.5%	2.8%
10.0	Ketuo	9.44	4.38	9.46	4.39	1.4%	2.5%
47.0	Epcos	42.4	4.51	42.1	4.54	1.5%	2.5%
100.0	Epcos	96.2	4.01	95.7	4.00	1.5%	2.4%
470.0	Chong	452.0	0.47	454.0	0.46	1.4%	5.2%
1000	Chong	925.0	0.32	931.0	0.33	1.5%	7.4%
4700	Ketuo	4450	0,17	4470	0.16	1.5%	10.5%

Table 6.4 – Results of the third test

All values that were measured with the Capacitor Analyzer are under the values obtained with the GCD Analysis. For instance, the 10.0 μF Ketuo Electrolytic Capacitor presented a capacitance of C_{cgd} = 9.44 μF when measured using GCD. The Analyzer indicated a capacitance of C_0 = 9.46 μF with a percentage uncertainty of δC = 1.4% or 0.13 μF , that is, C_0 = 9.46 $\mu F \pm$ 0.13 μF. This means that the C_{cgd} is inside the interval $C_0 - \delta C$ and $C_0 + \delta C$. This happens also for ESR and for all capacitors that were tested.

6.3 Final Conclusion

The equipment presented an outstanding performance under all tests that were carried out. The values of Capacitance and ESR as well as their uncertainties are under the expected values.

The theoretical approach was very accurate to describe the behavior of the proposed model and all the precautions that were taken to carry out precise and accurate measures led to a very satisfactory result.

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