Chapter 1
Capacitors

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1.1 Introduction to Capacitance

In 1745 a new physics and mathematics professor at the University of Leyden

(spelled *Leiden* in modern Dutch), *Pieter van Musschenbroek (1692 - 1791)* and his assistants Allmand and Cunaeus[1] from the Netherlands invented the 'capacitor' (electro-static charge or capacitance actually) but did not know it at first. His condenser was called the 'Leyden Jar' (pronounced: LY'duhn) and named so by Abbe Nollet. This Leyden jar consisted of a narrow-necked glass jar coated over part of its inner and outer surfaces with a conductive metallic substance; a conducting rod or wire passes through as insulating stopper (cork) in the neck of the jar and contacts the inner foil layer, which is separated from the outer layer by the glass wall. The Leyden jar was one of the first devices used to store an electric charge. If the inner layers of foil and outer layers of foil are then connected by a conductor, their opposite charges will cause a spark that discharges the jar. Actually, van Musschenbroek's *very* first *'condenser'* was nothing more than a beer glass!

A capacitor is a device that stores an electrical *charge* or energy on it's plates. These plates (a positive and a negative plate) are placed very close together with an insulator (dielectric) in between to prevent the plates from touching each other. A capacitor can carry a voltage equal to the battery or input voltage. Usually a capacitor has more than two plates depending on the capacitance or dielectric type.

Capacitance is present between any two adjacent charge-carrying conductors. A capacitor basically consists of two parallel plates separated by some distance. The size of plates, separation between the plates and medium between plates decide the magnitude of capacitance that can be stored by the capacitor.

C =(Area * constant of the medium in between the plates) / separation between the plates ....(1.1)

The material in between plates is called Dielectric material; some dielectric materials are air, paper, ceramic etc.,. When a voltage V is applied across the two metal plates the capacitor will become charged and the amount of charge Q will depend mainly on the voltage V. The capacitance C of the capacitor is the ratio of the charge acquired to the voltage applied or

$$C=Q/V \qquad \text{..............(1.2)}$$

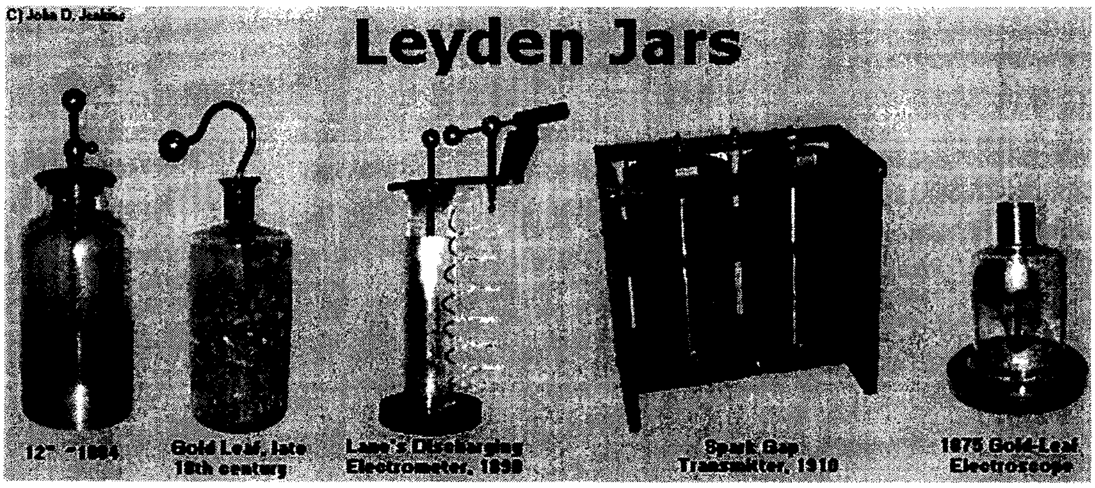
Where Q = charge in coulombs (or ampere – second)

V = Voltage applied in volts

C = Capacitance in farads

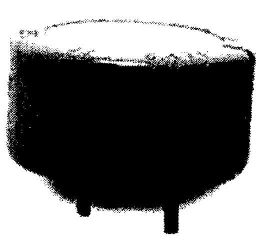
The farad is the capacitance of a capacitor that when charged with one "coulomb" of electricity (6,280,000,000,000,000,000 electrons) has an electric potential of one volt. This is such a large value that it is never used in the industry.

The capacitors, which are developed, recently can store up to hundreds of farads of capacitance. These are also super capacitors specifically used to replace in battery-operated circuits.



If larger the plate area and smaller the gap between the plates then larger the capacitance, which also depend on the type of insulating material between the plates. Replacing the air space with an insulator will increase the capacitance many times. The capacitance ratio using an insulator material is called ***Dielectric Constant*** while the insulator material itself is called just ***Dielectric***. If a Polystyrene dielectric is used instead of air, the capacitance will be increased 2.60 times.

Look below for a more detailed explanation for the most commonly used capacitors.



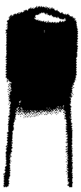
Super Capacitors[6] - The Electric Double Layer capacitor is a real miracle piece of work. Capacitance is 0.47 Farad (470,000 μF). Despite the large capacitance value, its physical dimensions are relatively small. It has a diameter of 21 mm (almost an inch) and a height of 11 mm (1/2 inch). Like other electrolytics the super capacitor is also polarized so exercise caution with regard to the break-down voltage. Care must be taken when using this capacitor. It has such large capacitance that, without precautions, it would destroy part of a power supply such as the bridge rectifier, volt regulators, or whatever because of the huge inrush current at charge. For a brief moment, this capacitor acts like a short circuit when the capacitor is being charged. Protection circuitry is a must for this type.

Electrolytic - Made of electrolyte, basically a conductive salt is placed between the plates in solvent. Coating a thin oxidation membrane in most common type of polarized capacitor uses aluminum electrodes.

Applications: Ripple filters, timing circuits, cheap, readily available and good for storage of charge (energy). Not very accurate, marginal electrical properties, leakage, drifting, not suitable for use in HF circuits, available in very small or very large values in μF. They will explode if the rated working voltage is exceeded or polarity is reversed, so be careful. When you use this type capacitor in one of your projects, the rule-of-thumb is to choose one which is twice the supply voltage. Example, if your power supply is 12 volt you would choose a 24volt (25V) type. This type has come a long way and characteristics have constantly improved over the years. It is and always will be an all-time favorite; unless something better comes along to replace it.

Tantalum - Made of Tantalum Pentoxide. They are electrolytic capacitors but used with a material called tantalum for the electrodes. Superior to electrolytic capacitors, excellent temperature and frequency characteristics. When tantalum powder is baked in order to solidify it, a crack forms inside. An electric charge can be stored on this crack. Like electrolytics, tantalums are polarized so watch the '+' and '-' indicators. Mostly used in analog signal systems because of the lack of current-spike-noise. Small size fits anywhere, reliable, most common values readily available. Expensive, easily damaged by spikes, large values exists but may be difficult to obtain. Largest in my own collection is 220µF/35V, beige color.

Polyester Film - This capacitor uses a thin polyester film as a dielectric. Not as high a

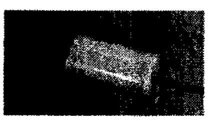


tolerance as polypropylene, but cheap, temperature stable, readily available, widely used. Tolerance is approx 5% to 10%. Can be quite large depending on capacity or rated voltage and so may not be suitable for all applications.

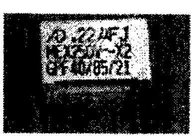
Polypropylene - Mainly used when a higher tolerance is needed then polyester caps

can offer. This polypropylene film is the dielectric. Very little change in capacitance when these capacitors are used in applications within frequency range 100KHz. Their tolerance is about 1%. Very small values are available.

Polystyrene - Is used as a dielectric. Constructed like a coil inside so not suitable for high frequency applications. Well used in filter circuits or timing applications used for



coupling signals up to hundred KHz or less. Electrodes may be reddish of color because of copper leaf used or silver when aluminum foil is used for electrodes.

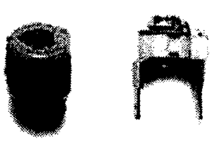


Metalized Polyester Film - Dielectric made of Polyester or DuPont trade name "Mylar". Good quality, low drift, temperature stable. Because the electrodes are thin they can be made very very small. Good all-round capacitor.

Epoxy - Manufactured using an epoxy dipped polymers as a protective coating. Widely available, stable, cheap. Can be quite large depending on capacity or rated voltage and so may not be suitable for all applications.

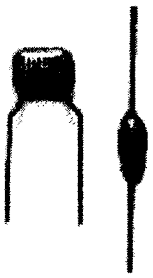
Ceramic - Constructed with materials such as titanium acid barium for dielectric.

Internally these capacitors are not constructed as a coil, so they are well suited for use in high frequency applications. Typically used to by-pass high frequency signals to ground. They are shaped like a disk, available in very small capacitance values and very small sizes. Together with the electrolytics the most widely available and used capacitor around. Comes in very small size and value, very cheap, reliable. Subject to drifting depending on ambient temperature. NPO types are the temperature stable types. They are identified by a black stripe on top.



Multilayer Ceramic - Dielectric is made up of many layers. Small in size, very good temperature stability, excellent frequency stable characteristics. Used in applications to filter or bypass the high frequency to ground. They do not exhibit a polarity. Multilayer caps suffer from high-Q internal (parallel) resonance - generally in the VHF range. The CK05 style 0.1μF/50V caps for example resonate around 30MHz. The effect of this resonance is effectively no apparent capacitance near the resonant frequency. As with all ceramic capacitors, be careful bending the legs or spreading them apart to close to the disc body or they may get damaged.

Silver-Mica - Mica is used as a dielectric. Used in resonance circuits, frequency

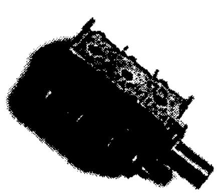


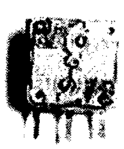
filters, and military RF applications. Highly stable, good temperature coefficient, excellent for endurance because of their frequency characteristics, no large values, high voltage types available, can be expensive but worth the extra dimes.

Adjustable Capacitors - Also called trimmer capacitors or variable capacitors. It

uses ceramic or plastic as a dielectric. Most of them are color coded to easily recognize their tunable size. The ceramic type has the value printed on them. Colors are: yellow (5pF), blue (7pF), white (10pF), green (30pF), brown (60pf). There are a couple more colors like red, beige, and purple which are not listed here. Anyway, you get the idea...

Tuning or 'Air-Core' capacitors: They use the surrounding air as a dielectric. I have





seen these variable capacitor types of incredible dimensions, especially the older ones. Amazing it all worked. Mostly used in radio and radar equipment. These types of capacitors usually have more (air) capacitors combined (ganged) and so when the adjustment axel is rotated, the capacitance of all of them changes simultaneously. The one on the right has a polyester film as a dielectric constant and combines two independent capacitors plus included is a trimmer cap, one for each side.

1.1 General Information on Capacitors

Capacitors store electrical energy in an electrical field. To understand the physical effects in the capacitor it is necessary to have basic knowledge about the electric field[5]. The fundamental formula for the capacitance of two flat parallel plates separated by a dielectric material is

$$C = (\varepsilon A \text{ X } 10^{12}) / (4\pi d \text{ X } 9 \text{ X } 10^{11}) \quad \ldots\ldots(1.3)$$

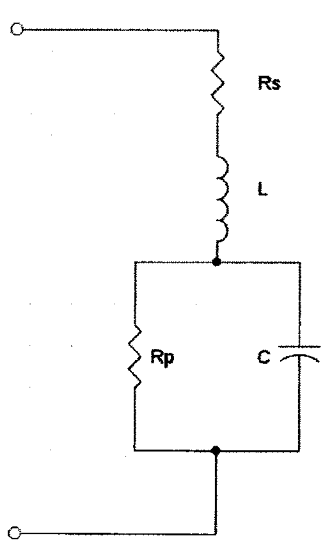
$$C = 0.0885\ \varepsilon A/d$$

Where C = capacitance in Pico farads (pF)

ε = Permittivity, or dielectric constant,

A = area of one plate in square centimeters,

d = distance between plates in centimeters.



When more than one plate is used the capacitance is multiplied by a factor (N – 1)

Where N is the number of plates.

$$C = (N - 1)(\varepsilon A * 10^{12}) / (4\pi d \text{ X } 9 \text{ X } 10^{11}) \quad \ldots\ldots(1.4)$$

The equivalent circuit of a capacitor may be represented as in figure where,

C = capacitance of capacitor,

Rs = resistance due to leads, plates and contacts,

Rp = resistance due to the dielectric and case material,

L = inductance of leads and plates of the capacitor.

Power factor:

The ratio of energy stored per cycle to energy wasted per cycle is called power factor of the material. For ideal dielectric it is independent of frequency. In a perfect capacitor with no dielectric loss $\delta = 0$. The power factor is

$$\cos \phi = 2\pi f\, RC \times 10^{-7} \qquad \text{.....................(1.5)}$$

Where f = frequency in KHz,

R= equivalent series resistance in ohms,

C = capacitance in μF

The effects of frequency on dielectric materials and capacitor assemblies:

At very low frequencies and also at very high frequencies there is an increase of loss, limiting the use of a capacitor at all frequency ranges with any dielectric.

At very low frequencies since the cycle time is very large, various forms of leakage in the dielectric material have sufficiently large time to become apparent, such as d.c. leakage currents and long time-constant effects.

At very high frequencies since the cycle time is very short dielectric polarization can not be complete, due to less time to become effective and therefore cause loss.

The impedance of a capacitor:

The current in a capacitor when an alternating voltage is applied is given by

$$I = 2\pi fCV \qquad \ldots\ldots (1.6)$$

Where C = capacitance in farads,

V = voltage in volts,

F = frequency in Hz

And the reactance is given by

$$Xc = -1/2\,\pi\, fC \text{ ohms} \qquad \ldots\ldots (1.7)$$

An ideal capacitor would have entirely negative reactance. In addition, inductance is also present in varying amounts and therefore as the frequency is increased the inductive or positive reactance increases, and above a critical frequency is increased the inductive reactance increases and above a critical frequency the capacitor will behave as an inductor. Every capacitor will resonate at some given frequency and have inductance and resistance, capacitive in one range of frequencies, resistive in another and inductive in still another.

1.2 Review of Different Measurement Techniques

Measurement of capacitance over wide frequency range is a very complex job even today. The impedance of any capacitor can be measured thinking it consists of a pure capacitance C_s in series with a pure resistance R_s or pure capacitance C_s in parallel with a pure resistance R_p. Usually at low frequency measurements series measurements are made and at high frequency measurements parallel measurements are made. Apart from these two techniques, one more technique gained prominence Charge-Based measurement. This techniques has both advantage and disadvantage of not using a frequency section. The advantage is not necessary to use frequency generator. In a project presented in California State Science Fair titled 'Using Capacitance to Distinguish between Living and Dead Cells'[42] it is shown that the frequency and the measured capacitance shown to be a linear function of cell number.

The first two techniques are very old and are reasonably accurate for wide range of frequency. As the circuits include discrete components and based on frequency the measurement it self has inherent limitations of component values used in construction.

1.3 Low Frequency Measurements

At low frequencies stray series impedances are small so measurement can be made as accurate as possible by careful selection of components. Usually bridge networks are used for accurate measurements.

1.3.1 The Carey – Foster bridge:

This bridge consists of inductor (L) with mutual inductance M and series resistor R in one arm, the other arm consists of capacitor Cs and series resistance Rs and in another arm a simple resistance is connected. The range of capacitance measurement of this bridge is upto about 10μF, and an accuracy of better than one part in ten thousand. Apart from the Capacitance measurement this circuit also gives the series resistance value Rs.

1.3.2 The Schering bridge:

This bridge consists of standard capacitor in one arm C, capacitor Cs and series resistor Rs in adjacent arm, in one arm a resistor Rv in parallel with variable capacitor Cv is placed and in remaining arm a simple resistor is placed. This bridge is of highest precision and has wide applications.

1.3.3 VFC:

VFC is a serial pulse train in the frequency range of 0 to 150kHz[19] with a non linearity error of less than 0.05%. The application notes from Philips Semiconductors describes how to measure values of a variable resistor or a variable capacitor using a microcontroller to measure the RC charge time to a constant threshold voltage[31]. A variety of these "one-shot" circuits are described and the accuracy of the various methods is measured. Sample programs for the 87C51 family are presented at the end of the article.

1.4 High Frequency Measurement

Capacitors do not behave the same as resistors. Whereas resistors allow a flow of electrons through them directly proportional to the voltage drop, capacitors oppose changes in voltage by drawing or supplying current as they charge or discharge to the new voltage level. The flow of electrons "through" a capacitor is directly proportional to the rate of change of voltage across the capacitor. This opposition to voltage change is another form of reactance, but one that is precisely opposite to the kind exhibited by inductors. Expressed mathematically, the relationship between the current "through" the capacitor and rate of voltage change across the capacitor is expressed as such:

$$i = C * (de/dt) \qquad \ldots\ldots\ldots(1.8)$$

The expression (de/dt) is one from calculus, meaning the rate of change of instantaneous voltage (e) over time, in volts per second. The capacitance (C) is in Farads, and the instantaneous current (i), of course, is in amps.

1.5 Future of Capacitors:

The future for capacitors looks good. A constant search is going on by companies like Murata, Kemet, etc. Kemet in particular is researching a new type of a dielectric substance called Niobium. Niobium Pentoxide (Nb_2O_5) offers a higher dielectric constant of 41 in comparison to Tantalum Pentoxide (Ta_2O_5) at 26. It implies that approximately 1.5 more CV (Capacitance x Voltage rating) can be obtained from the same amount of material, everything else being equal. This means much smaller capacitors with larger capacity, especially important in surface mount technology. Recently, a new type capacitor with very high capacitance has been developed with capacitance designated in Farads! Yes, you read it well, Farads. This type of *Electric Double Layer* capacitor is known as a "Super Capacitor". I am sure we haven't heard the last of it about this type.