CAPACITORS

1. Definition of Capacitance

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 electrical field.

1.1. The electrical field

Electrical charges of opposing polarity attract each other, electrical charges of equal polarity repel each other.

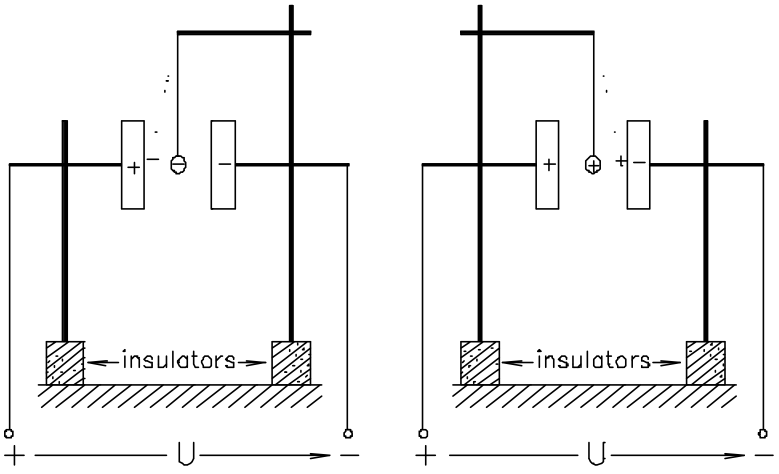

Fig.1.1.1.
Forces in an electrical field. A negatively charged particle is attracted to the positive side, a positively charged particle is attracted to the negative side.

The particle is subjected to the forces that exist in an electrical field. The strength of this electrical field is described by the electrical field strength E, unit V/m. One visualises the field as a number of field lines (arrows show from positive to negative).

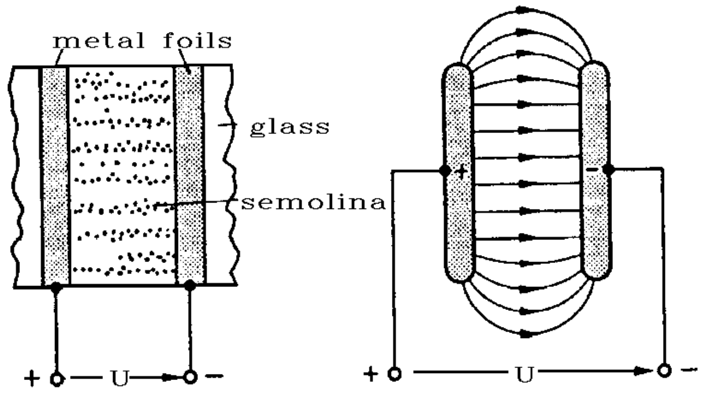

Fig. 1.1.2.

The electrical field can be made visible in the experiment.
Schematically the field is represented by field lines. The higher the density of the lines in an area, the higher the field strength.

The electrical field stresses even non-conductor molecules in such a way, that they **become polarized**. These are then called **molecular dipoles**.
This effect is called **static conduction**.

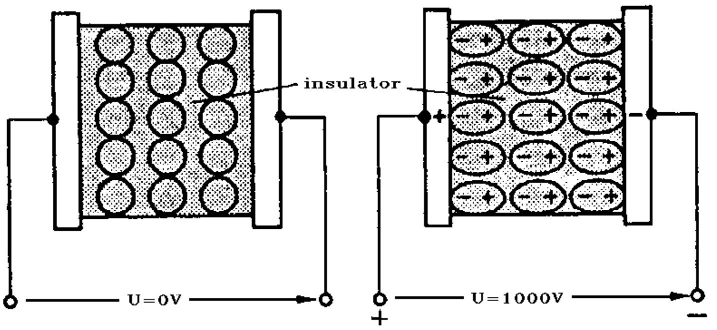

Fig. 1.1.3.
When the dielectric molecules are exposed to an electric field they become polarized and form dielectric dipoles.

When the field strength is too high (e.g. above 50 kV/cm), electrons are "torn" out of the molecular structure, producing moveable carriers of electrical charges. A current then flows and increases rapidly (avalanche effect). This effect is called flash-over or flash-through.

The electrical field strength which an insulator can withstand before flash-over occurs is called the dielectric strength.
Typical values of the dielectric strength of some materials: Dry air 30kV/cm, special insulator materials such as Polystyrol, Teflon, porcelain
may withstand 200kV/cm.
In air with normal humidity the safe spacing is normally selected with 5kV/cm.

1.2. Electrodes in the electric Field

Whenever there is a voltage between conductors there will be an electrical field. The distribution and position of the field lines depend on the shape of the conductors.

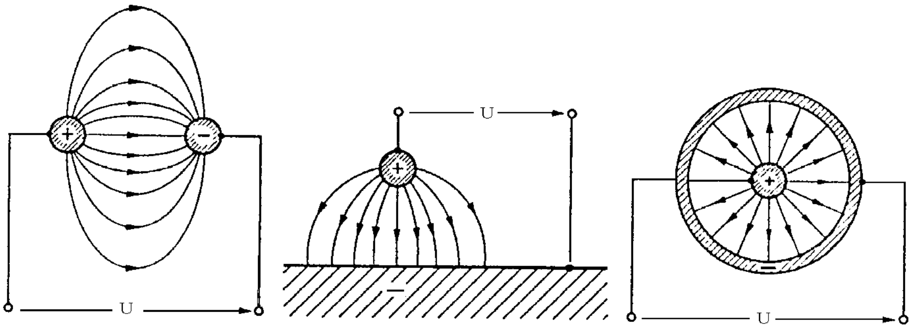

Fig. 1.2.1.
Different arrangements of the electric poles or electrodes and their resulting electrical fields

The applied voltage "pushes" electrons away from the positive plate. This moving and shifting of electrons is equivalent to a current into or out of a capacitor. Whenever the voltage is increased, more electrons are shifted. A current flows until the (new, stronger) electrical field has been built up. Such an arrangement represents a capacitor.

When a charged capacitor is connected to a resistor, the electrons shift back again and current flows through the resistor, producing heat (work). A capacitor is fully discharged when its voltage is zero.

The amount of electrical charge a capacitor holds if it is charged to a certain voltage is described by it "CAPACITANCE", which thus has the unit of Coulomb per Volts, which is given the name of FARAD.

1.3. Capacitors in Vacuum

Normally a capacitor is constructed of two conductive plate which are arranged insulated at a certain distance. The capacity depends on the area A of the plates and their distance d.
If the area is increased or if the distance is reduced the capacity increases.

This results in the relationship

$$C \approx \frac{A}{d}$$ A is electrode area, d is electrode distance

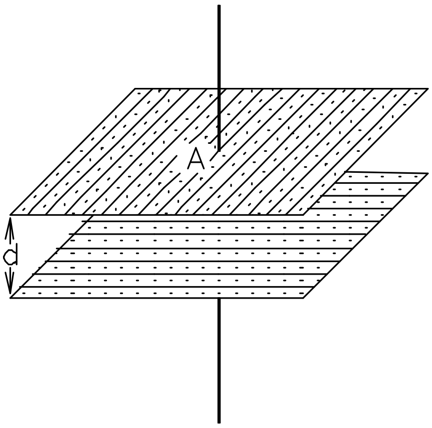

Fig. 1.3.1.
The capacitance depends on the area and the distance of the plates.

In order to make an equation of proportionality and to adopt the mechanical units of area and distance with the electrical unit of Farad, the so-called **DIELECTRIC CONSTANT** ε_o (Epsilon) is introduced.

$\boldsymbol{\varepsilon_o = 8.85*10^{-12}\ F/m}$

Now the capacitance of a capacitor can be expressed in terms of its mechanical dimensions:

$$C = e_0 * \frac{A}{d}$$

Units: C in Farad (F), A in m^2, d in m

To achieve a high capacitance either the area of the plates must be increased or the distance between the plates must be reduced. But the distance can not be reduced infinitely, because for a certain applied voltage a certain distance between the plates is required to avoid flash-over. In fact the distance between the plates depends on the max. voltage for which a capacitor is design. Therefore the dimensions of a capacitor will depend on its capacitance and its max. rated voltage.

A capacitor of one Farad would have huge dimension. In practice only fractions of this unit are required, thus the values are given in terms of µF, nF or pF.

1.4. Capacitors with Dielectric

The capacitance is also affected by the insulating material between the plates. As this material is a non-conductor it is called DIELECTRIC (Non-electric). The ability of the dielectric to increase the capacitance can be explained by the static conduction. The polarization of the molecular dipoles leads partly to a neutralization of charge on the plates. So more charge can be brought onto the plates with the same voltage.

The increase in capacitance due to a certain dielectric is described by the RELATIVE DIELECTRIC CONSTANT or RELATIVE PERMITTIVITY εr. It is a pure factor (the unit is 1).

The capacitance with dielectric is determined from the equation

$$C = e_r * e_0 * \frac{A}{d}$$

With $\varepsilon_r * \varepsilon_o = \varepsilon$ this can be written in a simplified form:

$$C = e * \frac{A}{d}$$

The dielectric is in fact the most important part of the capacitor, because it will control the properties to a large extend. Therefore the capacitors are mainly named after their dielectric. (E.g. Mica capacitor or Ceramic capacitor).

The relative permittivity of dielectric materials range between 1 and 100 000. Air has a $\varepsilon_r = 1$, thus behaves in a similar way as vacuum.

Some examples of relative permittivities of some dielectric materials:

Material:	e_r:	**Material:**	e_r:
vacuum	1	aluminium oxide	10
air	1	glass	10
paper	2	tantalum oxide	27
rubber	3	Condensa C	80
quartz	4	titanium dioxide	110
plexi-glass	4	barium titanate	20000
mica	5	Ferroxcube	100000

The higher the relative permittivity of a material, the smaller the area of the plates can be selected for same capacitance, thus the smaller the size of the capacitor.

But not only the relative permittivity of a material is of importance, also its dielectric strength. The higher the dielectric strength, the smaller the distance between the plates can be made for a certain voltage rating of a capacitor.

1.4. Interconnecting capacitors

In the same way as resistors capacitors can be combined in parallel or series connections, which produces then a resultant capacitance.

Parallel connection.

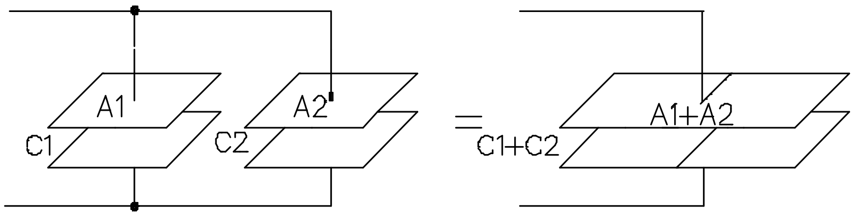

Fig. 1.4.1.
Capacitors in parallel add up their plate area.

When capacitors are connected in parallel it has the same effect as the summing up of the individual plate areas.

Thus the total capacitance of capacitors in parallel equal to the sum of the individual capacitors.

$$Cp = C1 + C2 + C3 + \ldots.$$

The total capacitance of capacitors in parallel is alway larger than any individual capacitance.

The total current flowing into the capacitors will distributed between the capacitors. The larger capacitor will take the larger current.

Series connection.

When capacitors are connected in series it has the same effect as the summing up of the individual plate distances.

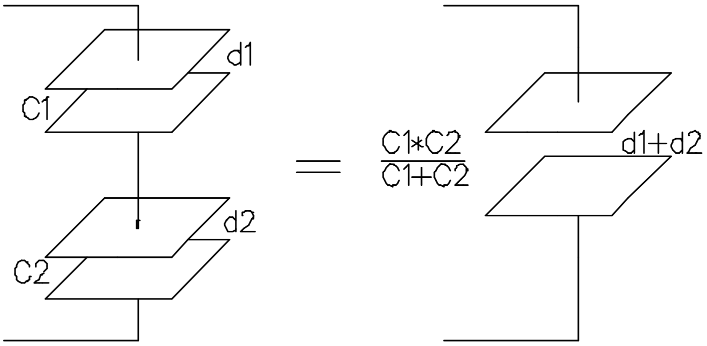

Fig. 1.4.2.
Capacitors in series add up their plate distances.

Since the plate distances of the individual capacitors add up, the total capacitances must be smaller.

$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots\ldots$$

For two capacitors this result in :

$$C_s = \frac{C_1 * C_2}{C_1 + C_2}$$

and for n equal capacitors in series:

$$C_s = \frac{C}{n}$$

When capacitors are connected in series, the total capacitance is always smaller than the smallest capacitance.

The current through all capacitors in series is the same. The voltage is divided. The largest capacitor holds the smallest voltage, the smallest capacitor holds the highest voltage. The sum of all voltages is equal to the applied total voltage.

2. Losses in Capacitors

Until now we have assumed, that all of the electrical charge applied to a capacitor is stored in it until it finds an external electrical path to discharge the capacitor. Such capacitor is storing electrical energy, it is not consuming any.

In practice this is not the case. There is loss of electrical energy during the storage period of the capacitor as well as during the charging and discharging process.

There are basically three physical types of losses:

Leakage losses.

As there is no ideal insulator, some charge will penetrate the dielectric, causing loss of charge on the plates, thus loss of energy.

These losses can be represented by a parallel resistor to the capacitor.

The leakage losses are mainly important in d.c. applications of capacitor.

Conductor losses.

When the capacitor is charged or discharge a current flows in the leads and in the plates. As these do not have 0 resistance, this current leads to a voltage drop and thus to a loss of electrical energy.

These losses can be represented by a series resistor to the capacitor.

The conductor losses are mainly important when the capacitor is operated at very high frequencies.

Dielectric Losses.

When a.c. voltages are applied to the capacitor, the molecular dipoles of the dielectric have to be re-polarized permanently. This produces some kind of friction in the dielectric, which produces heat. This heat energy appears as loss of electrical energy in the capacitor.

The dielectric losses can not definitely be represented by a series or parallel loss resistor, as they are not directly caused by an electrical quantity. Either a series or a parallel resistor can be used to represent the loss of electrical energy.

The dielectric losses appear when the capacitor is operated in a.c. circuits and their importance increases with the frequency.

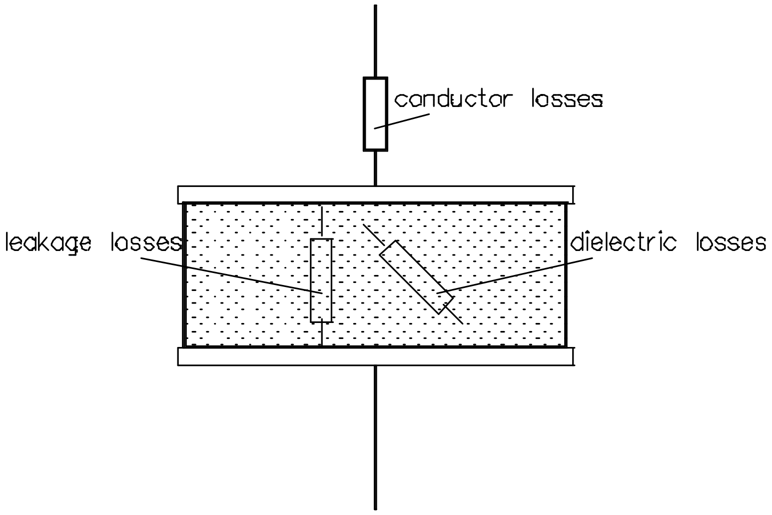

Fig. 2.1.
The effects of different types of losses in a capacitor can be represented by resistors.

Furthermore capacitors can have an inductive component, which is mainly caused by the coiling of the electrodes and by the terminal leads. Although inductance produces no power losses, they represent some unwanted effect, because they produce some resonant circuit in conjunction with the capacitance.

3. Characteristics of capacitors

Practically capacitors are described and labelled by some parameters, which inform the user about the physical characteristics of the capacitor.

Capacitance:

The capacitance is normally stated on every capacitor. In most cases numbers are used.

The colour code was also planned for capacitors, but is only little used today. If it is used, the figures and the multipliers give the capacitance in pF.
E.g. brown, black, red means $10*10^2$pF = 1000pF = 1nF.

Often the capacitance is given without unit, this means it is not stated if the value is in µF, µF or pF. Then the value given will either be in µF or pF. With some experience one can tell from the size of the capacitor which unit is more likely.

Examples of labelling the capacitance:

1000µF	full labelling, easy to read
1000	may be 1000µF or 1000pF =1nF, depending on the size and the constructions
102	is to be used like the colour code and means here $10*10^2$pF = 1nF
33n	means 33nF
3n3	means 3.3nF
n33	means 0.33nF

Voltage rating

The voltage rating gives the maximum normal operation voltage of a capacitor. When selecting capacitors, they should have a voltage rating which is higher than the highest expected voltage. Capacitors have a certain safety margin for occasional, unexpected exceeding of the rated voltage.

For a.c. capacitors the rated voltage some times means the RMS voltage, while sometimes the peak voltage is specified.

The voltage rating of a capacitor is normally labelled on it, but not always, especially not on small capacitors. Electrolytic capacitors have the voltage rating always labelled, because they are especially sensitive to excessive voltages.

Examples of labelling the voltage rating:

40V	full labelling, easy to read
1000/40	1000µF capacitor with a voltage rating of 40V

Some manufactures of capacitors give the voltage rating with letters, e.g. M, K, S etc. This is not standardized and the meaning of the letters differ for different manufactures. They can only be identified by using the manufacturer's data sheets.

The polarity

Polarized capacitors like the electrolytic capacitors will always have the suitable polarity specified. Normally this is done by indicating the plus (+) and the minus (-) terminal. Often only the minus terminal is indicated, the other one is the plus terminal.

Note that any interchange of the polarity leads to the destruction of the capacitor.

The outer electrode

It is useful to know which terminal is connected to the outer most electrode of the capacitor. This electrode may serve as some kind of screening to the capacitor. Therefore it is useful to connect this electrode to ground potential if possible.

Normally the outer electrode is indicated by a bar on the case.
Don't confuse it with a polarity indication! Such capacitors are not polarized.

Tolerance

Capacitors normally have larger tolerances than resistors.
Often the tolerance is not labelled on the element.

The following methods of labelling the tolerance are to be found:

- In full writing:(e.g. +50% -20%)
  Especially on electrolytic capacitors the tolerance range may be specified like this.
- By colour rings
  The same code is used as for resistors
- By letter code
  This code is not standardized and depends on the definition of the manufacturer.

Temperature range

Especially electrolytic capacitor are sensitive to excessive temperatures. Exceeding their temperature will either reduce the capacitance (low temperatures) or reduce their life span (high temperatures).

For large capacitors the temperature range may be specified on the case.

4. Fixed Capacitors technologies

Basically all capacitors consist of two electrodes with some kind of dielectric in between. But there are different technologies to produce the electrodes and the dielectric, where each one has its special advantages and disadvantages. Therefore different applications require different types of capacitors.

4.1. Vacuum Capacitors

This is the most basic form of capacitor. They consist only of two copper electrodes within a vacuum. The dielectric constant is therefore 1, so that vacuum capacitors will only be available for low capacitances.

The technology for vacuum capacitors is similar as for vacuum tubes. Therefore these capacitors are very expensive.

Advantages:
- Highest dielectric strength of all (high voltage)
- Minimum losses

Disadvantages:
- Low capacitance values only (<1nF)
- Large
- Very expensive

Application:
For high frequency applications within transmitters, where very high voltages occur and very low losses are required.

4.2. Foil Capacitors

The electrodes of these capacitors are aluminium foils, the dielectric is oil paper of different types of plastic foils. The package of electrode-dielectric-electrode-dielectric will be coiled up until the required capacitance is reached.

This type of capacitor provides reasonable electrical properties at reasonable volume and price. The electrical characteristics will depend on the type of dielectric used.

Advantages:
- Low series losses due to solid aluminium foil electrodes
- With suitable dielectrics available for high voltages

Disadvantages:
- relatively low capacitance/volume
- no self healing
- considerable inductive component due to coiled electrodes

Application:
HF applications e.g. in tuned circuits where low losses are required.

4.3. Film Capacitors

The construction of these capacitors is similar to the foil capacitor, except for the electrodes. It is an extremely thin film of aluminium, vapoured on the dielectric. Therefore the electrodes of these capacitors require no volume, making the capacitor relatively small. But the very thin electrodes have a considerable resistance, so that the capacitors have higher series resistances than foil capacitors.

The electrical properties of film capacitors depend mainly on the property of the dielectric.

Film capacitors are self healing:
In case of a break through (flash over) of the dielectric, the very thin aluminium film will immediately evaporate, insulating the damaged area. Every break through of the capacitor will therefore not destroy the capacitor, but will just produce a minor reduction of the electrode area (reduction of capacitance).

Advantages:
- Self healing
- higher capacitance/volume (than foil type)
- cheap

Disadvantages:
- relatively high series resistance

Application:
- General a.f and r.f. applications
- where non-polarized capacitors are required
- when no very low losses are required

4.4. Ceramic Capacitors

Ceramic capacitors use ceramic materials as dielectric. The electrodes are produced as a conductive metal film on the ceramic.

We have to distinguish two different types of ceramic dielectric:

Ceramic capacitors with low dielectric constant LDC:

This is the "old" type of ceramic capacitors. The ceramics have dielectric constants of 10 to 100. The ceramic material must have a certain minimum thickness, else it breaks easily. Therefore these capacitors are produced with low capacitance for higher voltages. They have very low losses, especially at high frequencies.

Advantage:
- low losses at high frequencies
- high dielectric strength (high voltage)

Disadvantage:
- relatively low capacitance/volume (large)

Application:
- r.f. resonant circuits
- high voltages (transmitters)

Ceramic capacitors with high dielectric constants HDC:

When ceramic materials with very high dielectric constants of up to 15 000 were developed, Ceramic capacitors gained more importance for low frequency applications. With this technology capacitors with relatively high capacitance at small size can be produced. The capacitance is even increased, when the capacitors are constructed in layer technology, having a big number of thin ceramic chips in one package, multiplying the capacitance.

Unfortunately these dielectrics have poor electrical characteristics: relatively high losses, non-linear capacitance, temperature dependent.
Therefore their use is restricted to certain low frequency applications.

Advantages:
- high capacitance/volume (small size)
- economical

Disadvantages:
- high losses at high frequencies
- non linear
- temperature dependent

Application:
- in a.f. circuits
- de-coupling
- uncritical timing

4.5. Aluminium Electrolytic Capacitors

Polarised Aluminium Electrolytic Capacitors.

In general aluminium electrolytic capacitors are constructed like all other capacitors consisting of a dielectric between two conducting layers. The first electrode (anode) of the aluminium electrolytic capacitor is an **aluminium foil** on the surface of which a layer of aluminium oxide has been electro-chemically deposited. This **aluminium oxide** film forms the dielectric and has a thickness of approximately O.0015 µm per Volt of working voltage. The dielectric constant of the aluminium oxide formed in this manner is approximately 10.

The second electrode (cathode) of the aluminium electrolytic capacitor is formed by a conducting liquid, the electrolyte. In order to apply voltage to the cathode a second aluminium foil is used which is normally known as the 'cathode'. In order to carry the **electrolyte** an absorbent paper layer is wound between the oxide coated aluminium foil (anode) and the other electrode (cathode). The liquid electrolyte can in normal situation conform to the surface shape of the two electrodes.

This design is for polarised capacitors.
Reverse DC voltages should not exceed 2V.
The 2V correspond to the natural oxide film which is always formed on aluminium foil and is thus present on the cathode. Application of reverse voltages in excess of 2V causes electro-chemical formation of oxide on the 'cathode' with simultaneous evolution of considerable volumes of gas and consequent damage to the capacitor.

Aluminium electrolytic capacitors of this basic design are only suitable for use with DC voltages or for superimposed AC voltages. In the latter case the DC voltage plus the AC ripple voltage may not exceed the operating voltage.

The active surface of the electrodes can artificially be increased by etching the aluminium surface to get a **rough surface**.

Due to the very thin dielectric (low d), the rough surface (high A) and the dielectric constant of 10, these capacitors have a very high capacitance per volume.

Problems arise from the electrolytic electrode:

The electrolyte will disintegrate the dielectric if the voltage is reversed, causing a short circuit between the electrodes.

The **electrolytic electrode is a relatively poor conductor**, producing series losses. The losses will increase strongly at low temperatures.

The aluminium-oxide dielectric requires constant **regeneration**. Electrolyte will be consumed for this process and is therefore consumed during the life span of the capacitor; we say "it dries out". This will reduce the capacitance and increase the series losses.

Consider the following rules when using electrolytic capacitors:

- Never reverse the polarity of a capacitor, it will be damaged and might even explode.
- Do not exceed the rated voltage for the capacitor.
- Do not store or operate electrolytic capacitors at high temperatures, this will reduce their life span.
- The capacitors may require reformatting of the dielectric, after they were off voltage for a prolonged time (stored).

Advantages:

- Very high capacitance/volume (small size)

Disadvantages:

- Polarised
- limited life span
- high losses
- Capacitance changes with time and temperature

Applications:

- When high capacitance is required
- DC applications
- Smoothing
- Coupling
- Uncritical timing

See additional information on electrolytic capacitors.

4.6. Tantalum Capacitors

The tantalum capacitor is also a polarised electrolytic capacitor. The positive electrode is of Tantalum, the negative electrode is a solid electrolyte of manganese-dioxide (MnO_2). The dielectric is Tantalum-oxide (Ta_2O_5), having a dielectric constant of 27.

Due to the very high dielectric strength of Tantalum-oxide the dielectric can be made extremely thin. This gives, in conjunction with the dielectric constant of 27, a very high capacitance/volume.

As the solid electrolyte used is a better conductor than that for the aluminium types, the losses are less, even at low temperature.

Note:
When exceeding the maximum voltage or when reversing the voltage, tantalum may be damaged and tend to produce a permanent short circuit of very low resistance. Often this results in a break down of the power supply.
So in case of an unidentified short circuit in a system, check for tantalum capacitors!

Advantages:
- Highest capacitance/volume of all (small size)
- Low losses (compared to aluminium type)
- Less temperature dependent

Disadvantage:
- Polarised
- More expensive (than aluminium types)
- More sensitive to excessive and reversed voltage
- May produce absolute short circuit when damaged

Applications:
- When small size at high capacitance is required
- DC applications
- Blocking a.c.
- Coupling
- Long timing

4.7. Summary of Characteristics and Applications

Properties of Capacitors

type ------ characteristic	metalized paper	Plastic		ceramic		mica	electrolytic aluminium tantalum	
		foil	film	LCD	HDC			
capasity range	10nF-10µF	1pF-1µF	10pF-10µF	1pF-500pF	100pF-1µF	1pF-1nF	500nF-50mF	5nF-5000µF
voltage range	50V-10kV	50V-1kV	25V-10kV	50V-50kV	20V-1kV	50V-50kV	3V-500V	2V-100V
tanä at f	$10^{-2}..10^{-3}$ 800Hz	$10^{-3}..10^{-4}$ 100kHz	$10^{-2}..10^{-3}$ 800Hz	$10^{-3}..10^{-4}$ 1MHz	$10^{-2}..10^{-3}$ 800Hz	10^{-3} 10^{-4} 1MHz	10^{-1} 10^{-2} 50Hz	$10^{-2}..10^{-3}$ 50Hz
capasitance per volume	high	Medium	high	Very low	high	very low	very high	highest
remarks	Self healing For power applications phase shifter, compenisation	Low losses, High precision. For tuned circuits	Self healing Good compromise between quality and volume. very commen	Low losses at high frequency For tuned circuits at high frequency.	Relativly small. Alternative to metallized foil but lower Q. High tempe rature coefficient	Rare, Expensive. High Q Used for high frequencies	Polarized, only for low frequencies Low Q, Rel. high leakage	Polarized, all parameters better than al. –types. Sensitive to voltage surges

The following diagram gives a rough impression how the losses of capacitors change with frequency.

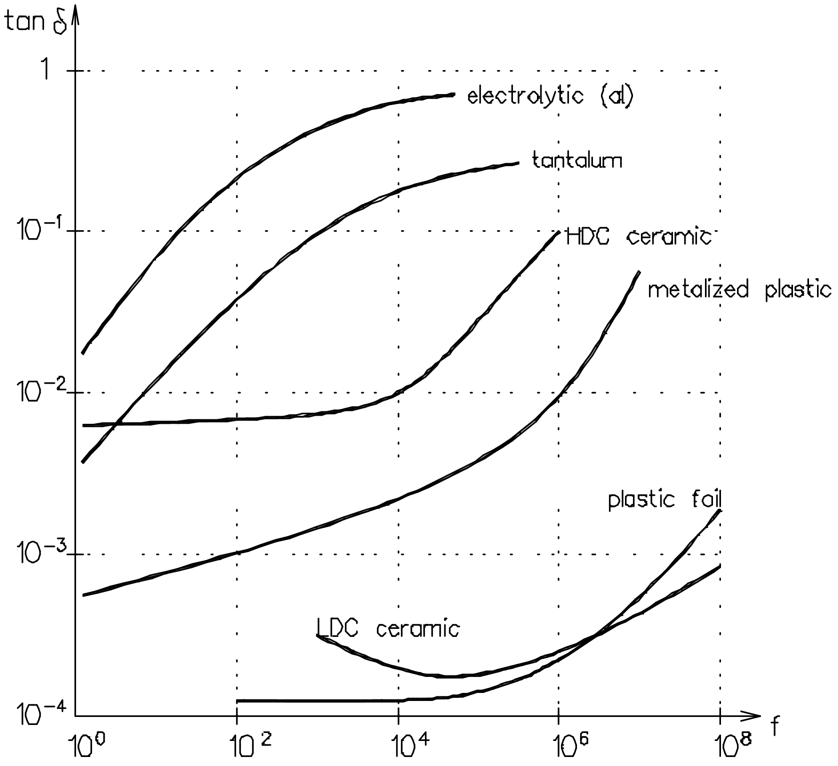

Fig. 4.7.1.
Losses of various capacitor types for different frequencies

5. Variable Capacitors

Mechanically variable capacitors are used to tune resonant circuits and filters in receivers, transmitters and signal generators.

They are available in the range from 10pF to approximately 500pF.

The capacitance is normally changed by varying the effective area of the capacitor's electrodes, for some times the electrodes' distances are varied.

Variable capacitors are available with a linear relationship between rotation angle and capacitance or with a square relationship, as it is required for tuned circuits.

"Butterfly" variable capacitors have two fixed sets of electrodes. The rotating part couples these electrodes more or less. This has the advantage that the signal must not be conducted to the rotating part.

Trimmer capacitors

Trimmer capacitors are used for screw driver adjustment of filters and resonant circuits. They are mainly ceramic type capacitors, but also air type and plastic foil type can be found in older equipment. The variation is generally achieved by changing the relative position of the electrodes to each other. As one electrode is rotated, the capacitance increases or decreases. Normally the trimmer capacitors have no dedicated position for maximum and minimum capacitance.

Capacitance Diodes (Varicaps):

Today often capacitance diodes are used for tuning purposes. They allow to control their capacitance by varying a d.c. voltage. In this way the capacitance can be changed by the factor 3 to 5. Maximum capacitance of up to 500pF are available.

The principle of function will be described with the diodes.

Advantages:
- no wear
- simple controls
- possibility for memory and remote control.

Disadvantages
- higher losses than other variable capacitors
- relatively small capacitance values
- non-linear voltage-capacitance relationship

Despite the disadvantages capacitance diodes are today widely used in electronic equipment, e.g. radio and TV tuners