Power Electronics Semiconductor Devices
Edited by Robert Perret

Chapter 5

Capacitors for Power Electronics

5.1. Introduction

Capacitors are essential components of power electronics systems. They can easily reach or exceed one third of the total volume of static converters, of which they are often the weak point. Their primary applications are in storage circuits, discharge, decoupling, filtering, resonance, snubbers, EMI shielding, etc.

The nature and the properties of the various materials used to build capacitors (dielectric, metallization, connections) have a direct influence on their properties. There are mainly three families of capacitors, each of them addressing a specific application or requirement. These are: metallized films capacitors, electrochemical or electrolytic capacitors and ceramic capacitors.

Historically, the first capacitors to have been used in electronics and in power engineering were paper capacitors. They were later abandoned in to low-voltage applications, for electrolytic capacitors and synthetic film capacitors. The paper based capacitors are still widely used when impregnated with a dielectric liquid that gives them sufficient voltage strength for applications for medium and high voltages. Finally, ceramic capacitors, using materials with very high dielectric constants, then appeared and are constantly finding new fields of applications.

Figure 5.1 summarizes the orders of magnitude of capacity of each of these capacitors, and their development today.

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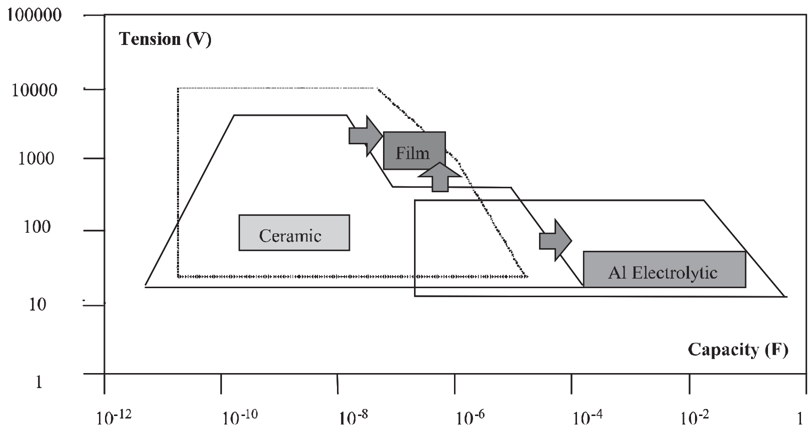

Figure 5.1. *Range of voltages and capacities of the different types of capacitors used in power electronics*

In the first part, we recall the main definitions and characteristics of such components as well as their constraints. We then describe in detail each of the different types. We will particularly expand on ceramic materials. It seems important to emphasize these materials, on the one hand because of their possible applications for hybrid integration and the development of new specific components; on the other hand because a large number of books and works are already devoted to films and electrolyte-type capacitors. At the end of the chapter we give a bibliography of useful references. In the penultimate section, we briefly describe some specific examples of applications of capacitors in power electronics. Finally, in conclusion, we will try to give trends for research and development (R&D) in the field of capacitors.

5.2. The various components of the capacitor – description

Whatever its type, a capacitor schematically consists of two conductive armatures separated by a dielectric material and linked by connections to the terminals of the external circuit (Figure 5.2). Applying a voltage to the terminals of the capacitor creates an electric field between the two armatures causing the polarization of dielectric and the storage of electrostatic energy. The polarization phenomena are depicted by the appearance of displacement currents within the dielectric and conduction currents in the armatures. These are collected by the connections and move towards the terminals of the capacitor. Hence, the electrical behavior of a capacitor cannot be reduced to the phenomena appearing in the dielectric material. The operation of a capacitor depends on physical phenomena occurring in its three components namely the dielectric material, the armatures and the connections.

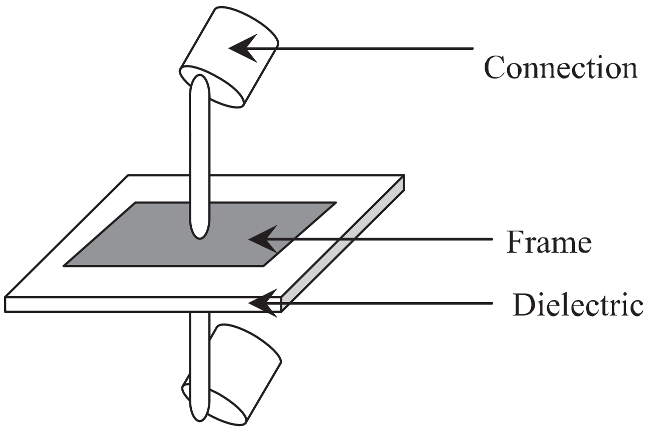

Figure 5.2. *Schematic description of a capacitor*

5.2.1. *The dielectric material*

A dielectric material is a substance able to be polarized when submitted to an electric field. It stores electrostatic energy whose density, for linear homogenous isotropic materials, is given by the relation:

$$w_e = (½)\ \varepsilon_0\ \varepsilon_r\ E^2$$

ε_0, ε_r and E respectively represent the permittivity of a vacuum, the relative permittivity of the dielectric material and the electric field. The density of stored energy is all the more high as the permittivity and/or the electric field are high.

5.2.2. *The armatures*

The armatures of a capacitor are used to apply an electric field to the dielectric and to collect current to drive it to connections. They also help to drive the heat outside of capacitor. Two large families of armatures exist. The so-called full armatures are separated from the dielectric. The armatures can also be made of a thin layer of metal deposited under vacuum on the dielectric material; these capacitors are called metallized armatures. In the case of so-called self-healing capacitors (mainly based on thin films), these armatures also play the role of a fuse. During a local breakdown of the dielectric material, they evaporate around the default (open circuit), thus avoiding the failure of the capacitor.

5.2.3. *Technology of capacitors*

The capacity of a plane capacitor is proportional to the permittivity of the dielectric material, the surface of the armatures and inversely proportional to the thickness of the dielectric. Thus, to obtain “geometrically” important capacities with acceptable dimensions, the dielectric folds on itself to achieve the geometry shown in Figure 5.3 where armatures alternate with dielectric layers.

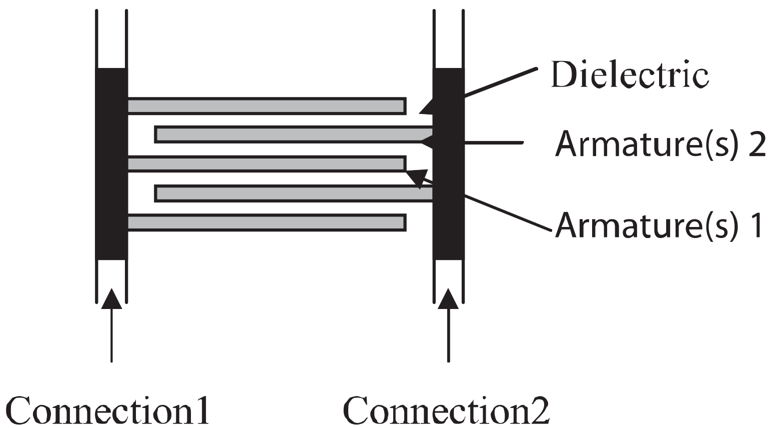

Figure 5.3. *Outline of a real capacitor*

In practice, this geometry is achieved either by stacking discontinuous dielectric layers (chervil technologies) (Figure 5.4), either by winding around an insulating core metallized dielectric films (dielectric and armatures) or winding all together dielectric films and metal sheets (frames) (Figure 5.5). The chervil technologies are particularly suitable for rigid dielectrics (ceramics, mica), but they are sometimes used for plastic dielectrics. The wound capacitors are only achieved with flexible materials (paper, polymers).

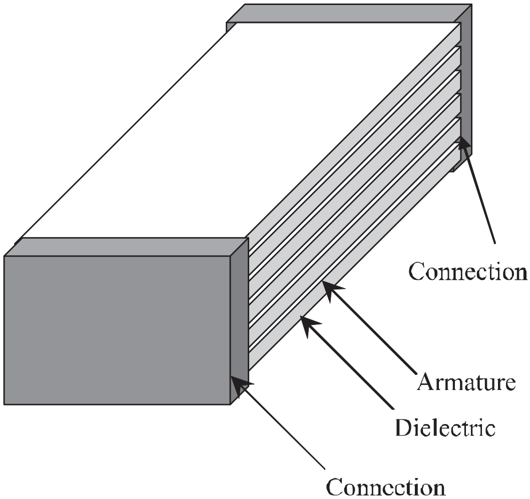

Figure 5.4. *"Chervil" technology*

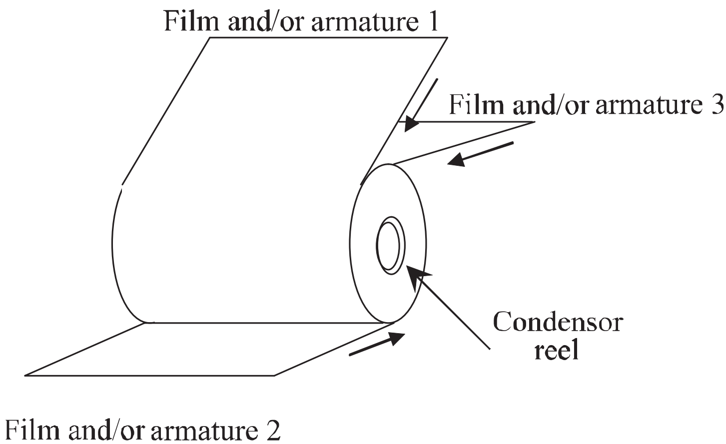

Figure 5.5. *Wound capacitor*

5.2.4. *Connections*

The link between the capacitor armatures and the external circuit is made through connection wires. The junction between the armatures and these connection wires depends on the type of armatures. It is created either through metal tabs (the contact is made at one point) or by welding all around winding (case of capacitors with overflowing armatures).

In the case of armatures of small thicknesses (case of metallized films), it must be ensured that the dielectric film is not damaged (by heating) during soldering operations (projection of molten metal for setting in parallel the elementary capacities formed by the capacitor coils in the case of a wound coil) and welding of connection wires. The nature and disposition of connection wires (internal or external return with regards to the core in wound capacitors) play a significant role in the distribution of currents and the value of the series inductor of the capacitor.

5.3. Stresses in a capacitor

When using a capacitor, it is important to take into account the constraints endured during its operation. Knowledge of the role it should play, qualities it must possess and stresses to which it will be submitted are of vital importance for an optimal design to the application. Before blaming the capacitor for the shortcomings of a system, we must ensure that its choice fits the requirements and the function it should meet. However, the use of a capacitor in power electronics applications is submitted to a number of constraints related to the waveform and to the amplitude of the applied voltage applied and the characteristics of the dielectric material, armatures and connections.

5.3.1. *Stresses related to the voltage magnitude*

One of the important properties of a capacitor concerns its dielectric strength. It is a complex problem because the breakdown may have very different origins. The voltage strength of a capacitor depends not only on the disruptive strength of the dielectric but also on the temperature, the magnitude and the waveform of the applied voltage, and on its packaging (connectors and armatures). The latter have a direct influence on the distribution of the electric field applied to the dielectric. They can lead to an enhancements of the local electrical field, especially along the metallization. These fields are all the more intense as the thickness and/or the radius of curvature of the armatures are low. Unless using other tricks (increase of the armatures' thickness and of the curvature radius of edges), the dielectric cannot be used close to its intrinsic dielectric strength. The operating voltage of a capacitor must be less than a value of partial or total destruction of the dielectric. This is called "derating" (Figure 5.6).

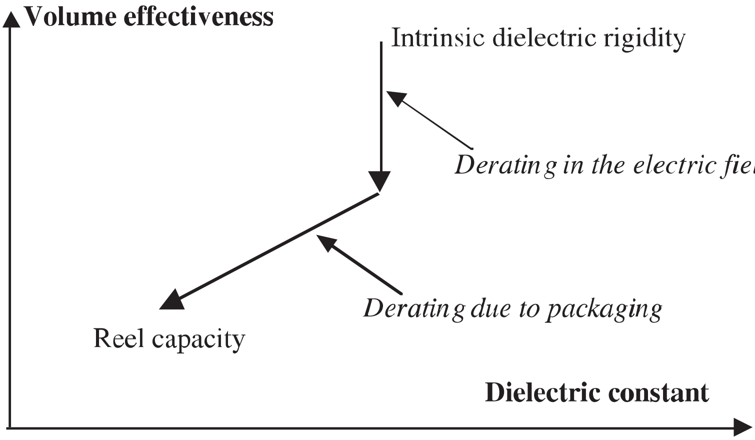

Figure 5.6. *Example of derating of a capacitor*

5.3.2. *Losses and drift of capacity*

Applying an alternative voltage to the terminals of a capacitor may in certain circumstances lead to heating and therefore loss of energy. These losses depend on the voltage waveform, the nature of the frames and the environment of the capacitor.

There are two types of losses:

– ohmic: these are due to armatures and connections, they depend on temperature and frequency. The use of thick armatures and large contact surface between the frames and connections minimize them;

– dielectric: these are the result of conduction in the dielectric (leakage current, losses by conduction) and polarization phenomena in the dielectric, following the application of electric field (losses by polarization). These dielectric losses lead to the drift of the capacity of the capacitor.

The losses in a capacitor are often represented by electrical equivalent circuits, in series or parallel (Figure 5.7). Such representations are only valid for sinusoidal operation of angular frequency ω. In Figure 5.7a (parallel equivalent circuit), resistors R_a and R_{dp} correspond to the ohmic and dielectric losses. The concept of dielectric losses factor $\tan \delta_d$ (δ_d is the complementary angle to the angle of phase shift between current and voltage) is also used to characterize a capacitor (Figure 5.7b). Moving from a parallel equivalent circuit to a series equivalent circuit (R_a, R_{ds}, C_s) (Figure 5.7c) conforms to relations:

$$\tan \delta_d = (1/C_p R_{ds} \omega) = C_s R_{ds} \omega$$

with:

$$C_s = C_p (1 + \tan^2 \delta_d) \text{ and } R_{ds} = R_{dp} [\tan^2 \delta_d/(1 + \tan^2 \delta_d)]$$

Total losses (ohmic and dielectric) in a capacitor are often described using the notion of equivalent series resistance $R_{se} = R_{ds} + R_a$, or global losses:

$$\tan\delta = \tan\delta_d + R_a C_s \omega$$

As the parameters of all the representations above are frequency dependent, their use with non-sinusoidal voltages, which is often the case in power electronics, is possible only through frequency splitting (Fourier transforms). However, it is rare that the principle of superposition principle applies, since the response of dielectric materials with frequency is rarely linear.

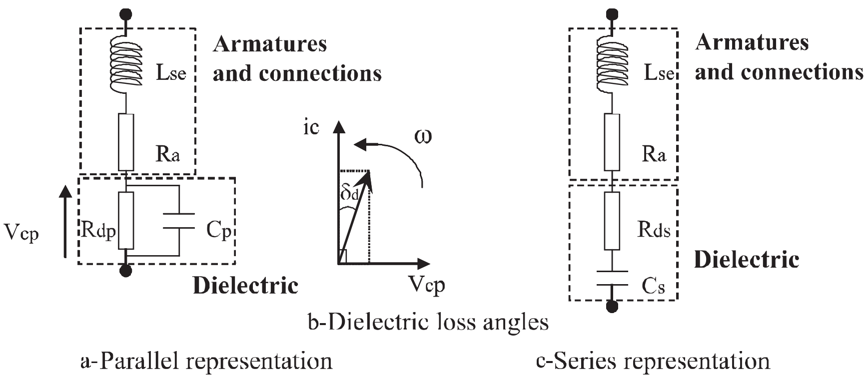

Figure 5.7. *Equivalent electrical circuit of a capacitor under sinusoidal operation*

5.3.3. *Thermal stresses*

If the losses generated in the capacitor are larger than the amount of heat it can dissipate, a heat imbalance occurs, which can lead to the failure of the capacitor. Dielectrics are generally excellent insulators, electrical as well as thermal. It is therefore difficult to dissipate the heat. In an attempt to solve this problem, different techniques are used: space around the capacitor, use of appropriate color for housing, use of heat spreaders, etc.

As mentioned previously, the losses generated in a capacitor may be determined in the first approximation, through the split of the electrical signals in their harmonic components and by calculating the average power dissipated by each component. For a harmonic voltage of angular frequency ω, knowledge of dielectric losses factor $\tan \delta_d$ is used to evaluate the power $P_{average}$ dissipated in the dielectric:

$$P_{average} = C\, \omega\, V_{rms}^2 \tan \delta_d$$

C and V_{rms} are respectively the capacity of the capacitor at angular frequency ω and the effective value of the voltage applied to its terminals.

For a plane capacitor, the power dissipated in the dielectric is:

$$P_{average} = (\varepsilon_0\, \varepsilon_r\, A/e)\, \omega\, V_{rms}^2 \tan \delta_d$$

A, ε_r and e are respectively the surface of the armatures, the relative dielectric permittivity and its thickness.

The amount of heat removed by natural convection is proportional to the surface it exposes to the environment. The heating of capacitor ΔT compared to the atmosphere is such that:

$$\Delta T \;\alpha\; (\varepsilon_r/e)\, \omega\, V_{rms}^2 \tan \delta_d$$

Thus, the heating of the capacitor decreases with the thickness of the dielectric and increases with permittivity and frequency. The ohmic induced losses, i.e. the contribution of power P_a dissipated in the resistance R_a linked to the current in armatures and connections, have to be added to the heating.

5.3.4. *Electromechanical stresses*

When a voltage is applied to a capacitor, armatures with opposed charges attract each other through a Coulomb force that derives from the electrostatic energy stored in the capacitor. The result is a compression of the dielectric. These forces may cause, if the material allows, a deformation of the dielectric material and may lead to a reduction of its dielectric strength. For an alternative voltage, the compressive force is itself alternative, which can lead to mechanical fatigue of the dielectric resulting in an electromechanical failure.

5.3.5. *Electromagnetic constraints*

The magnetic forces acting between armatures or between connections of the capacitor may have main consequences on current collection. These forces are proportional to the square of the current (i^2). They also depend on the geometry of the system, in particular, they are inversely proportional to the distance between armatures. In a given application, these forces are even more important as the peak value of the current applied to the capacitor is high. In capacitors intended to provide high current pulses, particular attention must be given to the design of armatures and output connections to avoid tearing. On the other hand, self inductance of a capacitor (due to its armatures and its connections) can lead to overvoltages in its terminals at large variations in current (di/dt) or frequency. It may also have serious consequences on the life of the component.

5.4. Film capacitors

As mentioned previously, film capacitors can be either full armatures, metallized or dielectric flexible materials.

5.4.1. *Armatures*

5.4.1.1. *Full armatures*

Full armatures can be overflowing or centered. In the case of overflowing full armatures, metal sheets are sometimes placed on the right or left of the longitudinal axis of the winding, leaving a margin of a few millimeters on each side (Figure 5.8). The connections are made by compression of metallic sheets or projection of a metal that is welded to the connection wires.

In the case of a system with centered full armatures, armatures are centered in the longitudinal axis of dielectric films (Figure 5.9). Each armature has a width smaller than that of the dielectric to maintain a margin on each side of the winding. The output connections are created using metal tears connected to each armature. These strips are then linked together to be connected to the terminals of the capacitor.

The orders of magnitude of frames and film dimensions are identical in both systems. The thickness of each frame is between 1 and 10 µm and the thickness of the plastic film from a few µm to 20 µm, according to the effective current and voltage to be held. For high values of the nominal voltage, several dielectric films of low thickness are preferred to one thick film.

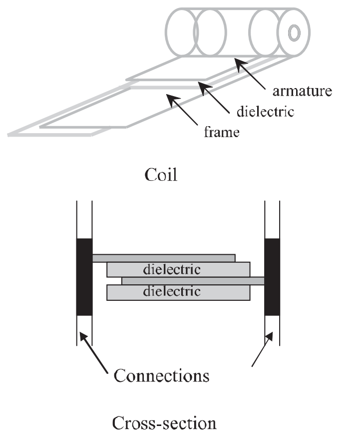

Figure 5.8. *Structure of a capacitor with overflowing full armatures*

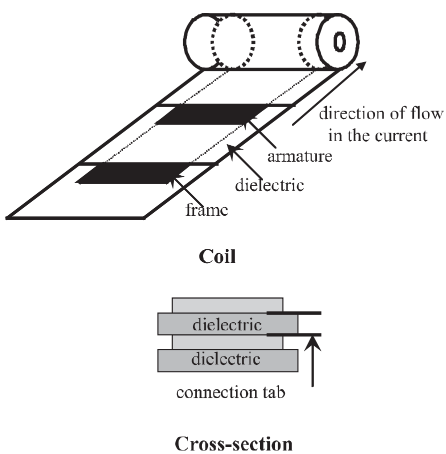

Figure 5.9. *Structure of a capacitor with centered full armatures*

5.4.1.2. *Metallized armatures*

The armatures of a metallized capacitor are obtained by deposition, under vacuum on the dielectric film, of a thin layer of metal (aluminum or zinc) of ten to a few tens of nm thickness. While operating, if a short circuit appears at a point in the dielectric, the thickness of the coating is such that the energy produced by the local breakdown of the dialectic material causes evaporation of the metallization around it. The default is therefore isolated from the healthy part of the capacitor at a cost of a slight decrease in capacity that it is self-healing. As for the thickness of the dielectric, it is between 5 and 12 μm (Figure 5.10).

The metallization of a dielectric is carried out so as to leave a margin of insulation of a few mm on each side of the winding to prevent short circuits. On the opposite side of this margin, the thickness of the deposit is being strengthened in order to facilitate the connection to the *armatures* (Figure 5.11).

To achieve the capacitor, two metallized films are wound around an insulating support (core) so that their strengthened edges are not on the same side of winding. A lateral shift between the two films facilitates the collection of currents, i.e. contact with the coating (metallic coating obtained by projecting a molten metal) on both sides of the winding. The metallization of film 1 is in contact with the coating (also called "shooping") on one side of the winding and metallization of film 2 is in contact with the other side. The coating connects in parallel all of the winding turns. The output connections are made by welding two wires on coatings on both sides of winding.

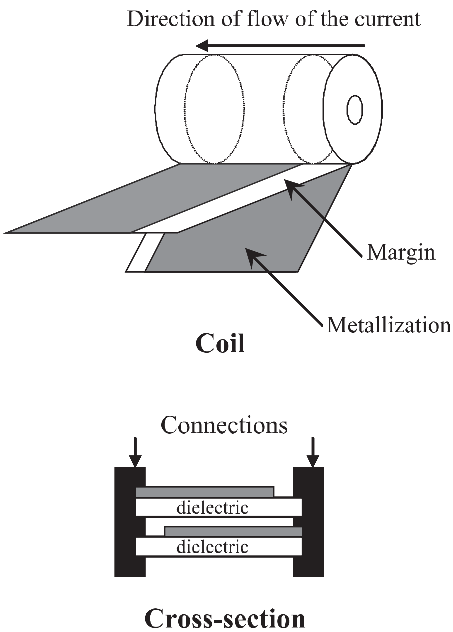

Figure 5.10. *Structure of a capacitor with metallized armatures*

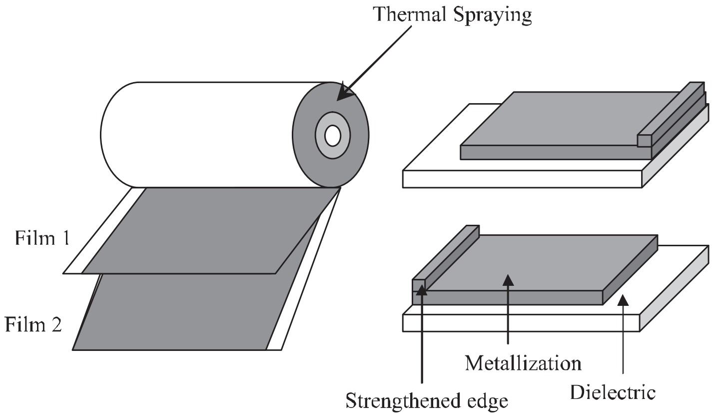

Figure 5.11. *Structure of a capacitor with metallized armatures and strengthened edges*

5.4.2. *Dielectric materials*

The main materials used in the manufacture of film capacitors' films are polypropylene, polyester (polyethylene glycol ethylene, known as Mylar) and polycarbonate. All these materials have nearly the same permittivities. The use of one or the other depends on the operating conditions (mechanical, thermal, etc.). Polyester and polycarbonate can be used between -55°C and 125°C, while polypropylene can be used between -40°C and 100°C (or 85°C). However, polypropylene is the preferred dielectric due to its low cost, the stability of its properties (low losses and low drift of capacity) and its high dielectric strength (around 500 MV/m (500 V/µm!) for films by 10 µm film thickness). All these things make polypropylene widely used.

For high temperature applications, other materials like Teflon or polysulfon are used. They can operate at temperatures above 150°C, but due to their cost, their use is limited.

5.5. Impregnated capacitors

The capacitors with full armatures can also be impregnated. In this case, there are two dielectric materials, a solid and a liquid are used. The liquid dielectric makes it possible to replace the air (or any air gap) across the whole structure of the capacitor and especially at the frame edges, thus avoiding the initiation and development of partial discharges which affect the lifetime of the capacitor.

This impregnation technique was used in the early 20th century with basic materials such as paper and mineral oil (all-paper capacitor). The paper, composed of cellulose, is easily impregnated by mineral oil but has fairly high losses ($10^{-3} < \tan\delta < 10^{-2}$) for normal operating conditions (frequencies and temperatures), so the mean fields for a paper-oil structure are relatively low (around 20 V/µm). The use of polychlorinated biphenyls (PCBs) in the 1930s made possible a service gradient of 20 to 30 V/µm and prolonged the timelife of these capacitors.

Thanks to progress in polymers science, a new generation of capacitors began in 1966 with the use of paper together with polypropylene films whose electrical properties are remarkable (dielectric strength three to five times the one of paper and dielectric losses less than 2×10^{-4}): they are called mixed capacitors. These elements, made of alternating layers of polypropylene and paper, have led to a significant rise in average field service (35 to 40 V/µm), a reduction of losses and an increase of reactive power density, compared to paper capacitors.

New techniques, allowing service operation to a value of up to 50 V/µm, reduced dielectric losses ($\tan\delta \sim 10^{-4}$) and volume, removing the paper, have emerged as a result (in the 1980s): "all-film" polypropylene capacitors. The difficulties encountered for impregnation while removing paper, which served as a wick for impregnation in mixed capacitors have been resolved by the use of rough films and/or corrugated frames leading to a better dissemination of impregnation inside the structure.

The impregnating liquids have also contributed to improve the performance of capacitors. For environmental reasons and public health (toxicity), the use of PCBs has been strictly regulated or even prohibited in some countries. They are gradually being replaced by new liquids or mixtures that meet both environmental and electrical requirements, and are products that have very good dielectric properties and "gassing" properties (i.e. a good ability to absorb gas generated by the action of the electric field or as a result of partial discharges). The main dielectric liquids currently used for impregnation are MDBT (mono-dibenzyl toluene known as UGILEC) and PXE (phenyl xylyl ethane).

5.6. Electrolytic capacitors

The two armatures are, in this type of capacitor, made of metallic sheets (aluminum in general) immersed in a slightly acidic conductive liquid called an electrolyte. For manufacturing, an electrochemical reaction (anode oxidation) is produced between one of the armatures (aluminum foil of thickness between 50 µm and 100 µm), which plays the role of anode and the electrolyte, applying a positive difference of potential, and this leads to the formation of a thin layer of aluminum oxide (Al_2O_3) with a dielectric constant $\varepsilon_r \sim 8$.

The main feature of these capacitors is to be polarized. The foil and oxide (Al_2O_3) filed over are intended to form the anode and the dielectric of an electrolytic capacitor. It is a system obtained by winding together several different sheets:

– the anode foil with the dielectric layer, which is in contact with an electrolyte (the same as the one used in the forming phase of alumina) ensuring a continuous regeneration of the alumina layer;

– a second foil of aluminum with a thickness of about 30 µm constitutes the cathode;

– a blotting paper of a few tens of µm is inserted between the two previous foils, it serves as a reservoir to the electrolyte, which is in direct contact with the alumina layer deposited on the anode.

To increase the energy density, today's technologies use etched aluminum foils before undergoing anodic oxidation (Figure 5.12). Also, the loss factor of this type of capacitor depends on the purity of aluminum used: the weakest loss factor being obtained for the most pure aluminium foils.

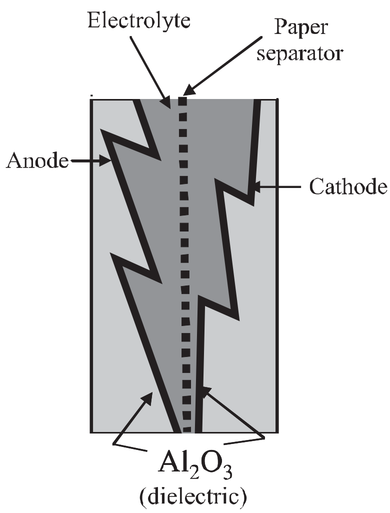

Figure 5.12. *Schematic showing the structure of an aluminum electrolytic capacitor*

The anode and cathode foils are connected to the terminals of the capacitor with strips introduced during the winding (Figure 5.13). To minimize series resistance and inductance (ESR and ESL respectively) as much as possible, strips are inserted and combined all together to the terminals of the capacitor.

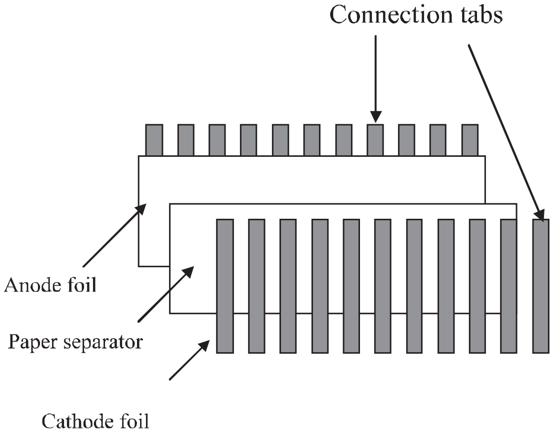

Figure 5.13. *Mode of connection to the terminals in the electrolytic capacitors*

A peculiarity of aluminum electrolytic capacitors is that they are polarized. Applying a reverse voltage between the anode and the cathode can generate gas inside the package whose pressure can lead to the explosion of the component if it is not equipped with a release valve.

5.7. Modeling and use of capacitors

The capacitors used in power electronics are subject to very severe stresses directly related to switching. They are flowed by currents that have on the one hand, very high rates of changes, sometimes exceeding 500 A/µs, and on the other hand, a very large harmonic content. In most of the power electronics systems, the switching frequency is larger than 20 kHz. Regarding low power systems, soft switching converters may operate at frequencies above 10 MHz (e.g., electronic ballast of discharge lamp). The use of capacitors in converters is mainly for input and output filtering of the DC or low frequencies voltages. They can also be found in resonant converters, quasi-resonant converters, multilevel converters, as well as in systems to help the commutation (snubbers with or without power dissipation).

5.7.1. *Limitations of capacitors*

Losses in capacitors are mainly due to stresses (voltage and temperature and flowing currents). In power electronics, all conditions are encountered together and make the capacitor a fragile component of the system.

The main limitation is the current which, on the one hand may lead to surges caused by inductive phenomena in the capacitor's internal connections, and on the other hand, due to its magnitude, can lead to electrodynamic efforts capable of destroying the capacitor.

The operating temperature also limits its performance. Indeed, the maximum operating temperature is relatively low ($\theta_{max} \leq 85°C$) and the ageing of a dielectric is temperature dependent. Losses in dielectric insulation, Joule losses in armatures, connections and in the case (eddy current) contribute to increase the loss of its performance.

Recent work has revealed the non-homogenous distribution of currents in capacitors according to their frequency. The knowledge of this phenomenon enables us to understand more precisely the "hotspots" of the capacitor flowed by high frequency currents and to determine its internal inductance. This can reduce, using appropriate internal connections, the internal inductance for a cylindrical geometry. We will now discuss the procedure to establish this type of model.

5.7.1.1. *Fine model*

Consider a cylindrical metallic film capacitor (Figure 5.14) wound on an insulating mandrel, where the coatings on the basis of the cylinder collect conduction current from the armatures. The geometry results in the symmetry of distribution of fields and currents in the capacitor. The conductors outside the winding are in fact arranged symmetrically in relation to the axis of symmetry of revolution of the capacitor.

The electrical and electromagnetic values are assumed to be sinusoidal. They will therefore be dependent on the pulse ω and the radius r of the capacitor. Let:

– $\underline{I}(r,\omega)$ be the current in the coating;

– $\underline{J}_{sc}(r,\omega)$ the surface density of current flowing in the coating;

– $\underline{B}(r,\omega)$ the magnetic induction.

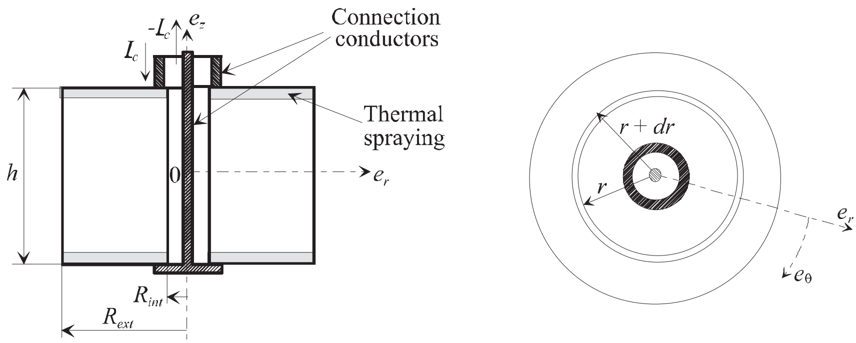

Figure 5.14. *Outline of capacitor*

The winding dimensions are as follows: R_{ext} external radius, R_{int} radius of the mandrel and h its height. The central connection imposes the following conditions on the current $\underline{I}(r,\omega)$ directed along the axis e_r running through the loop (C_1):

– on the external side of the coil $\underline{I}(R_{ext},\omega) = 0$;

– on the external side of the mandrel $\underline{I}(R_{\text{int}},\omega) = \underline{I}_C$,

where $\underline{I}_C$ is the current supplying the power capacitor. The boundary conditions on the coating give a relationship between the orthoradial magnetic field $\underline{B}(r,\omega)$ in the winding and the current $\underline{I}(r,\omega)$:

$$\underline{B}(r,\omega) = -\frac{\mu_0}{2\pi r}\underline{I}(r,\omega)$$

If C is the total capacity of the capacitor, the surface capacity per area unit of the coating is $\gamma = \dfrac{C}{\pi(R_{ext}^2 - R_{\text{int}}^2)}$. The conductance per area unit $\underline{Y}_s(\omega)$ is setting a series connection of a conductance $j\gamma\omega$ due to the capacitive effect and a conductance G_s associated with dielectric losses and Joule losses in metallization.

The surface admittance is expressed by the relationship:

$$\underline{Y}_s(\omega) = \frac{j\gamma\omega}{1 + j\dfrac{\gamma}{G_s}\omega}$$

In addition, the alternating magnetic field $\underline{B}(r,\omega)$ will in turn create electromotive forces and thus disturb the distribution of the potential in the capacitor. In the plane (O, e_r, e_z) of the capacitor, the circulation of the electric field between two points, located at the same distance r from axis (O, e_z) and placed on a different coating, and the voltage drop resulting from the impedance of the coating $\underline{Z}_{sc}(r,\omega)dr$ between two circular crowns of radius r and $r + \mathrm{d}r$ (Figure 5.14) is equal to the temporal variation of magnetic flux created by $\underline{B}(r,\omega)$ on the surface limited by the contour ***abcda*** (Figure 5.15). The abovementioned Faraday law is written:

$$-\underline{\xi}(r+dr,\omega)+\underline{\xi}(r,\omega)-2\underline{Z}_{sc}(r,\omega)\underline{I}(r,\omega)dr=-j\omega h\underline{B}(r,\omega)dr$$

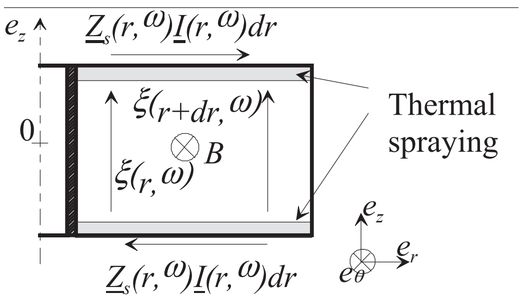

Figure 5.15. *Circulation of the electric field in a loop*

When dr tends to zero, the equation becomes:

$$\frac{f\underline{\xi}(r,\omega)}{fr}=-2\underline{Z}_{sc}(r,\omega)\underline{I}(r,\omega)+j\omega\underline{B}(r,\omega)$$

with $\underline{Z}_{sc}(r,\omega)dr = \frac{\underline{Z}_{sc}}{2\pi r}dr$ elementary impedance between crowns depending on the surface impedance of coating which itself may be written in the form $\underline{Z}_{sc} = \frac{(1+j)\rho_{sc}}{\delta_{sc}}$ with $\delta_{sc} = \sqrt{\frac{2\rho_{sc}}{\mu_{sc}\omega}}$ where μ_{sc} is the magnetic permeability of coating and ρ_{sc} its resistivity.

In the case of a zinc coating, then: $\mu_{sc}=\mu_0=4\pi\ 10^{-7}$ H/m and $\rho_{sc} = 5.8\cdot10^{-8}$ Ωm.

The distribution of potential between the two coatings is associated with the current surface density running through the capacitor, so:

$$\underline{J}_s(r,\omega)=\underline{Y}_s(\omega)\underline{E}(r,\omega)$$

The surface current density $\underline{J}_s(r,\omega)$ is also associated with the current $\underline{I}(r,\omega)$ by the relationship:

$$\frac{\partial \underline{I}(r,\omega)}{\partial r}=-2\pi \underline{J}_s(r,\omega)$$

Combining equations, we obtain:

$$r^2\frac{\partial^2 \underline{B}(r,\omega)}{\partial r^2}+r\frac{\partial \underline{B}(r,\omega)}{\partial r}+\left[\frac{r^2}{\delta_c^{\,2}}-1\right]\underline{B}(r,\omega)=0$$

with δ_c equivalent to a skin thickness in the capacitor:

$$\delta_c=\left[\frac{-1}{\underline{Y}_s(\omega)[2\underline{Z}_{sc}+j\omega h\mu_0]}\right]^{\frac{1}{2}}$$

To solve this equation, we note J_n and Y_n as the Bessel functions of order n, respectively of the first and second species. Taking into account the boundary conditions, the solutions of the equation are written for a return to the center:

$$B(r,\omega)=\frac{\mu_0\underline{I}_c}{2\pi R_{\text{int}}\Delta}\left[Y_1\left(\frac{R_{ext}}{\delta_c}\right)J_1\left(\frac{r}{\delta_c}\right)-J_1\left(\frac{R_{ext}}{\delta_c}\right)Y_1\left(\frac{r}{\delta_c}\right)\right]$$

with $\Delta=Y_1\left(\frac{R_{\text{int}}}{\delta_c}\right)J_1\left(\frac{R_{ext}}{\delta_c}\right)-J_1\left(\frac{R_{\text{int}}}{\delta_c}\right)Y_1\left(\frac{R_{ext}}{\delta_c}\right)$

On the other hand, we can determine the current density in the capacitor:

$$\underline{J}_s(r,\omega)=\frac{\underline{I}_c}{2\pi R_{\text{int}}\delta_c\Delta}\left[Y_1\left(\frac{R_{ext}}{\delta_c}\right)J_0\left(\frac{r}{\delta_c}\right)-J_1\left(\frac{R_{ext}}{\delta_c}\right)Y_0\left(\frac{r}{\delta_c}\right)\right]$$

The equation shows that the current density depends in part on the ratio between the outside radius of the capacitor and of the "pseudo-skin thickness δ_c". The total impedance of the capacitor is derived from the expression of the distribution of the current density in the capacitor, where l_s and r_s represent the inductance and the resistance of the external connections of the capacitor. The total impedance is then written as:

$$\underline{Z}_{tot} = \frac{\underline{J}_s(R_{int},\omega)}{\underline{Y}_s(\omega)\underline{I}_c} + jl_s\omega + r_s$$

5.7.1.2. *Impedance of the wound capacitor*

The representation of the impedance of a capacitor as a function of the frequency is given in Figure 5.16. As in the classic model, the impedance decreases with a slope of -20 dB per decade up to its resonance frequency. However, beyond this frequency, the impedance increases with a slope close to 20 dB per decade. From this example around 1.6 MHz, there is a fairly clear variation of the module of the impedance and of its phase. This variation, which is repeated to a lesser degree at 3 MHz, corresponds to a minimum of the expression Δ given in 15 and hence to a maximum of the current density $\underline{J}_s(R_{int},\omega)$.

These increases reflect, in the winding, changes of phase of $\underline{J}_s(R_{int},\omega)$ which reflect the existence of loop currents as shown in Figure 5.17. Thus, capacitors wrapped in metal films behave in a similar manner to the anti-resonant circuits or microwave cavities.

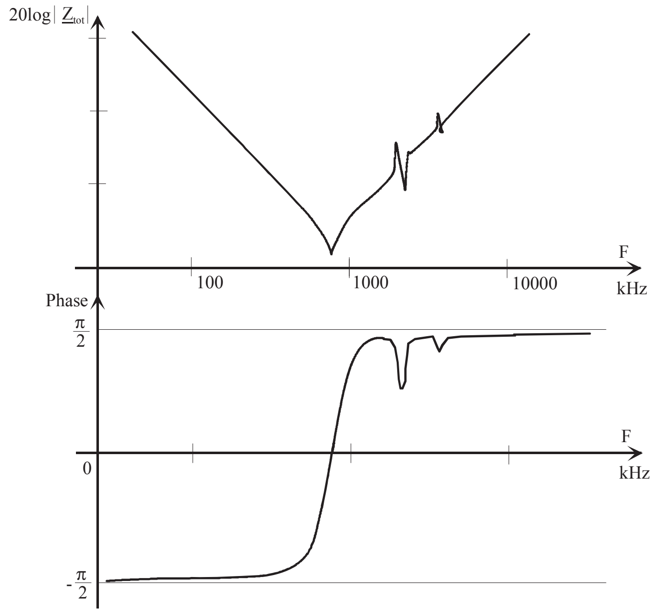

Figure 5.16. *Impedance of the capacitor*

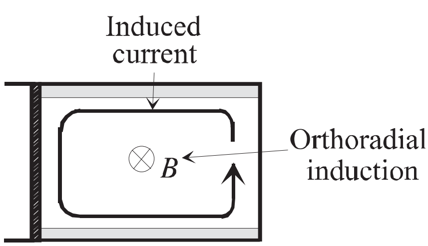

Figure 5.17. *Currents induced in the winding*

5.7.1.3. *Distribution of current density in the winding*

It is possible to reveal the distribution of current density in the capacitor depending on the distance r from the center for different frequencies (Figure 5.18). For low frequencies, the current density is homogenous in the capacitor; beyond its resonance frequency, it becomes larger inside (close to the mandrel) and outside of the winding, involving very significant local heating.

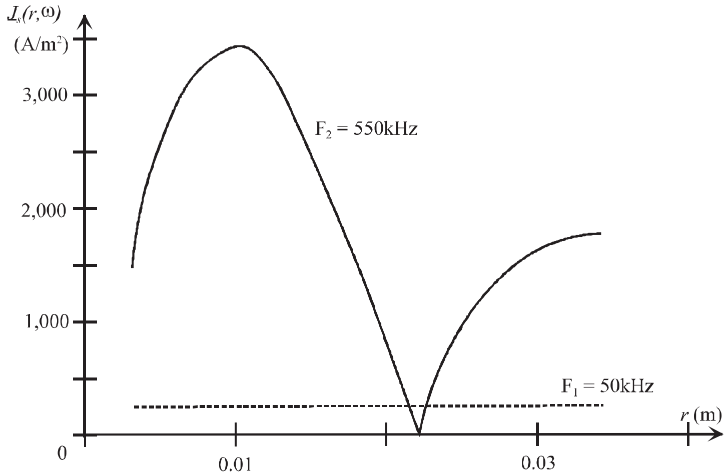

Figure 5.18. *Distribution of current density depending on the distance to the axis of symmetry of winding for two frequencies*

The use of capacitors with symmetric connections, while desirable to minimize self inductances and radiated fields, is not always possible because of the manufacturing technologies used. There are often, in power electronics designs, wound capacitors with structures as shown in Figure 5.19 (return conductors being simple wires made of insulated copper). To take these asymmetries into account, the former model must be changed. Thus, a misalignment of 3 mm of the return conductor leads the current density flowing through the winding (in an amount not exceeding the wire) in the vicinity of the return wire to be multiplied by a factor of 300 for a capacitor of 72 mm diameter.

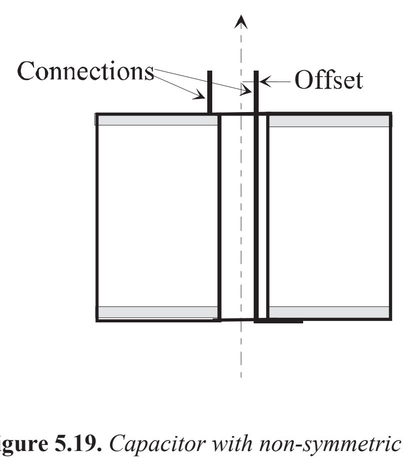

Figure 5.19. *Capacitor with non-symmetric return*

5.7.1.4. *Self-inductance of capacitor*

The behavior described by the impedance equation can show the resonant frequency of the capacitor for a return conductor in the center. It is easy to obtain, for a same type of capacitor (same geometry and same physical characteristics), its impedance with an external return. To do this, new connection conditions must be imposed: $\underline{I}(r=R_{int},\omega)=0$ and $\underline{I}(r=R_{ext},\omega)=-\underline{I}_c$. The model shows that an external return is preferable to a central return: the resonance frequency is twice as high for an external return as for a return to the center, implying that the self inductance in the first case is 1.414 ($\sqrt{2}$) times lower.

Starting from this model, it is also possible to seek a capacitor, which will minimize inductance, changing its geometric parameters (h, R_{int} and R_{ext}). Two types of simple geometries are eligible for this result: *flat capacitors* (diameter of winding > length of winding) and *annular capacitors* (large R_{ext} and R_{int}).

5.7.2. *Application of capacitors*

Power electronics systems require capacitors for:

– filtering stages or decoupling;

– resonant circuits (resonant load, quasi-resonant converters, storage of electrostatic energy, etc.);

– snubber circuits.

For each domain, some background on the characteristic wave shapes of currents that can flow in the capacitors are given.

5.7.2.1. *Filtering capacitors (or decoupling)*

The filtering capacitors are designed to minimize the voltage ripples. They operate under almost quasi-continuous voltage.

At the converter input, in most cases (choppers, switching power supplies, inverters, PWM rectifiers with zero voltage switching, active filters, etc.), they can filter the power network, rectified or not. In the first case, their value is very large considering the low frequency of the network. Simultaneously, they also serve as bypass for commutation cells, in order to recreate at their terminals a voltage source as ideal as possible to limit the voltage surges due to the switching. Electrolytic capacitors are mainly used here and capacitor films to a lesser extent. Sometimes, whatever the technology (same or mixed), they are placed in parallel to reduce the internal stray inductances.

At the output, only a filtering function is needed, according to the quality required. Depending on the nature of the voltage (DC or AC), either continuously or alternative, electrochemical capacitors or capacitor films are used.

According to the preceding section on the limitations of capacitors, it may be demonstrated that, by an appropriate internal connection, it is possible, from a wound capacitor, to make an almost perfect decoupling. This capacitor is called a "quadripolar capacitor".

5.7.2.2. *The quadripolar capacitor*

On a metallized film capacitor wound around a core, cylindrical revolution connections, with simultaneous returns to the center and to the periphery, are carried out as presented in Figure 5.20. This component becomes quadripolar including two accesses, AD and EH. The currents flowing in the capacitor coil do not distribute homogenously as their frequency increases. In particular, HF currents propogate toward the center of the coil (CC' area) for a connection ABFD and to its periphery (DD' area) for a connection EBFH, which contributes to an almost perfect HF decoupling between the two circuits.

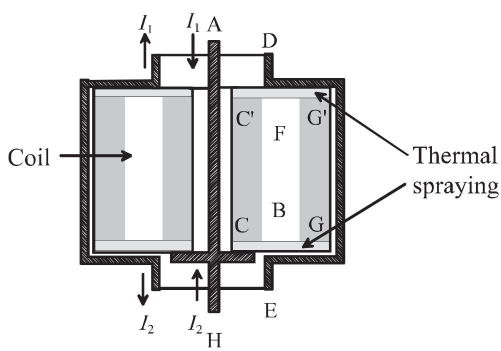

Figure 5.20. *Structure of the quadripolar capacitor*

The physical model of this quadripolar capacitor is shown in Figure 5.21. The quantities r_s and l_s represent the resistors and inductors of external connections, M_{12} the residual mutual inductance between the two connected circuits and $V_{CC'}$ and $V_{GG'}$ the sources of potential differences between points C and C' on the one hand and G and G' on the other. These are functions of the distribution of current density $\underline{J}_s(r,\omega)$ in the capacitor and surface conductance of winding films $\underline{Y}_s(\omega)$.

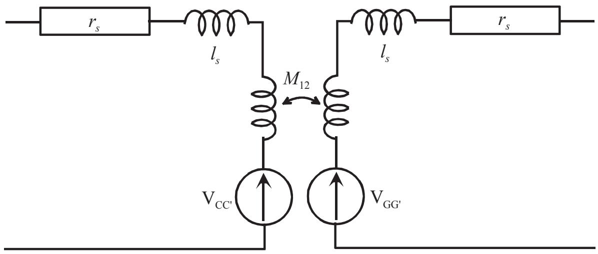

Figure 5.21. *Physical model*

The characterization of decoupling capacitors is described by its "insertion loss" (rated *PI*) depending on the frequency. This quantity is defined as follows: $PI(dB) = 20\log\frac{V_1}{V_m}$ with V_1 the voltage on a 50 Ω load without the capacitor and V_m the voltage on the same charge connected with the capacitor (Figure 5.22).

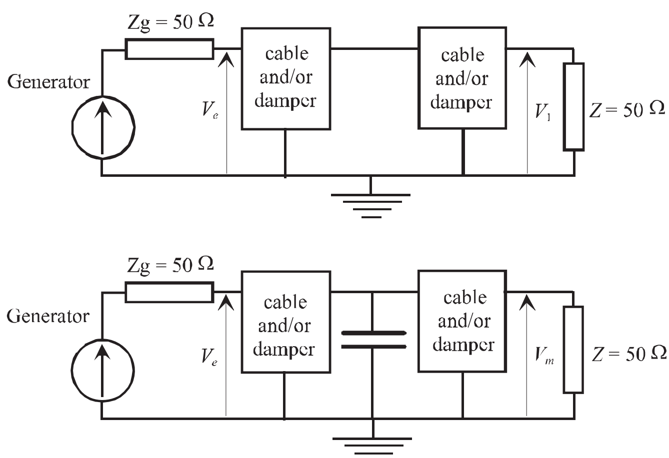

Figure 5.22. *Measurement of insertion losses*

In Figure 5.23, the comparison between the *PI* of a quadripolar capacitor and those of a classical dipolar capacitor shows that at high frequency the first one keeps its capacitive characteristics. This type of capacitor could be used to greatly reduce differential mode electromagnetic disturbances.

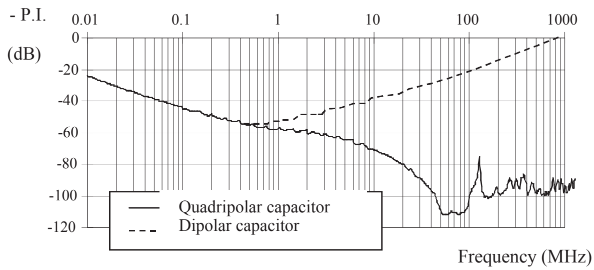

Figure 5.23. *Insertion losses of 10 µF capacitors*

5.7.2.3. *Resonant capacitors*

Capacitors used in resonant converters, quasi-resonant converters or structures where the capacitive element is directly involved in the conversion, are subject to very important current intensities at high frequencies. The shapes of waveforms applied are almost AC and DC voltages and alternative voltages. In these cases, the dielectric losses and the temperature increases are large. Their ability to endure heat must be a choice criterion.

5.7.2.4. *Switching capacitors*

The capacitors used for snubbers are subject to large current pulses during switching. Here, the value of internal inductance is a key parameter and must be as low as possible. The connections must be made very carefully. As the switching cell is a source of large electromagnetic fields, the capacitor must be shielded if its electromagnetic susceptibility is low.

5.8. Ceramic capacitors

The current interest for ceramic materials is mainly associated, on one hand, with the possibilities of sustaining high permittivity values and, on the other hand, thanks to the development of technological processes to decrease the size of these components hence favoring their integration in power electronics systems. In the following, we will draw a quick overview of the properties of these materials to enable the engineer to choose the appropriate component on a rational basis. In a first step we describe the main characteristics of these materials. Then, their methods of manufacture (from material to component) are presented. Finally the main types of capacitors currently available on the market and some of their possible applications in power electronics systems are given.

5.8.1. *Definitions*

5.8.1.1. *Ceramic materials*

The word ceramic comes from the Greek word "keramos", which means "potter" or "potter's clay". It comes from the ancient Sanskrit root "burn". The definition given generally for a ceramic is "product obtained by action of fire on a material derived from the earth". These are inorganic materials contrary to polymers (based on carbon chemistry).

5.8.1.2. *Nature of chemical bonds*

From a physical point of view, ceramics are made of crystals, inside which – in the first approximation – the individual atoms are bonded by ionic type connections. The nature of atomic bonds is therefore also different from that between atoms in a polymer which is a type of low-valence (dipole, or hydrogen or van der Waals type).

The ionic bond presents a spherical symmetry leading to a non-directionality of the valence; their binding energy is thus very high (about 750 kJ/mol (compared to the tens of kJ/mol for polymers)), giving them unique properties: a high hardness, a high melting point, a low electrical conductivity and high permittivity. This last property is of particularly interest here.

5.8.1.3. *Dielectric properties*

In crystals, and contrary to polymers, electric dipole moments are usually tightened. The dipoles are part of the crystalline structure: they are the structure. The electric field polarizes these materials by inducing dipole moments. The charges' displacement from their position of equilibrium changes the solid dimensions. The properties of these materials may no longer be described by vector quantities but rather by tensors. Relations between the electrical parameters (Polarization, P, Displacement, D, etc.) are generally linear (but may not be: see the type II components (section 5.8)) but involve the three space components of the electric field E.

5.8.1.4. *Piezoelectricity and ferroelectricity*

The consequence of the previous assertion is that the physical properties of the crystals are related to their crystalline structure. Of the 32 existing symmetries, 20 of them are piezoelectric. When these materials are compressed, they develop a potential difference and, conversely, if an electrical voltage is applied, a mechanical deformation appears. Among these 20 classes, 10 of them are polar, i.e. they have an electrical polarization even in the absence of an applied external electric field. Their dipole moment is spontaneous and generally small and fixed.

A certain category of polar crystals are called ferroelectrics: here the polar axis, support of a permanent dipole, is mobile in the crystal lattice under the influence of an external electric field high enough. The ferroelectric materials have a polarization Po in the absence of field. The high dielectric constant of these materials allows us to produce capacitors with a high capacity per volume unit, thereby reducing their size.

5.8.1.5. *Temperature coefficient of a component*

Some physical properties are intrinsic to this type of material (or components). The main property is the temperature coefficient of the capacitor (CTC). This is defined by:

$$CTC = \frac{1}{C}\frac{dC}{dT}$$

with C the capacity and T the temperature.

This coefficient must be as low as possible except when a temperature drift of the circuit in which these components are placed has to be compensated. CTC may then be negative, positive or zero (the literature talks about NPO components).

CTC can also be written according to the intrinsic properties of materials and becomes in this case the temperature coefficient of permittivity, $CT\varepsilon$ such that:

$$CT\varepsilon = \frac{1}{\varepsilon}\frac{d\varepsilon}{dT} + \lambda$$

with ε the permittivity and λ the thickness changes of the material with temperature.

When the material is not isotropic, or when it is very sensitive to temperature, these two factors (CTC and $CT\varepsilon$) are very different. In ceramics, anisotropic materials by definition, these two factors are different. Changes in the capacity with temperature are due to:

– the existence of impurities;
– changes in the dimension of the structure;
– changes in polarizability (due to the change of structure).

5.8.2. *Methods of producing ceramics*

The process of manufacture of ceramics, like the ones used in power electronics, requires a large number of steps. They are summarized in Figure 5.24.

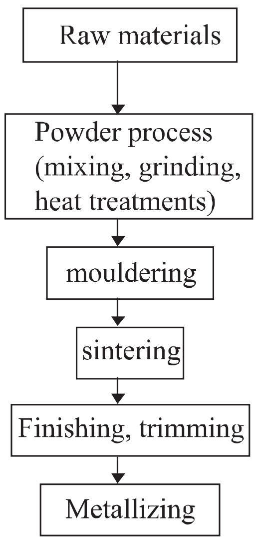

Figure 5.24. *Steps for manufacturing of ceramics*

5.8.2.1. *Powder process*

The manufacturing technology is used to obtain a material with specific properties of perfectly controlled dimensions and of course at the lowest cost. The material properties are mainly affected by the chemical composition, but also by the size and distribution of powders, porosity, uniformity, etc., which depend greatly on the synthesis method.

Two distinct processes may be used for the preparation of powders, the chemical method and the traditional solid/solid method.

5.8.2.1.1. The solid/solid method

This is a mix of powdered raw materials of simple oxides (transition metals or others) in proportions calculated to achieve the desired composition. The mixture can be made dry or wet: the slurry. The slurry is shaken to homogenize the mixture which, after drying, is calcinated. The mechanical grinding treatment can reduce the particle size, increase the specific surface and increase the reactiveness of the powder during the sintering. To obtain the appropriate result, it is often necessary to carry out several runs of grinding-calcination.

5.8.2.1.2. The chemical method

This technique aims to develop powders of mixed oxides, in the adequate proportions, directly from “precursor” powders (carbonates, oxalates, formiates, etc.). The steps are as follows:

– precipitation in solution of the “mixed” precursor corresponding to the composition desired;

– thermal decomposition of the original salt and transformation into an oxide.

This method of preparation at room temperature allow to control the shape, size and distribution of the powders and thereby improve the densification, reproducibility and stability of the properties and among them the electrical properties of the ceramics. This prevents many grinding and burning operations.

5.8.2.2. *Shaping*

It is during this operation that “raw” ceramics are produced, which can be broadly described as a stacking of grains mechanically linked by an organic binder. The powder must first undergo a granulation which increases the fluidness. This operation consists of incorporating an organic link in the oxide powder to give it plasticity and to ensure a sufficient cohesion of the raw ceramic. The choice of shaping crucially depends on the geometric structure of the component to be produced. In the case of “bulk ceramics”, the set (oxide powder + binder) is pressed. For manufacturing multilayer ceramics, a “tapecasting” process is used. This shaping is industrially used for the manufacture of components from thin strips (a few mm). This operation consists of the suspension of a dry powder in an aqueous or organic media. The stability of this suspension is provided by the addition of a scattering agent. The production and handling of thin strips of large surface requires the introduction into the slurry of organic binders and plasticizers. These products give to the dry band the mechanical rigidity and flexibility necessary for its handling. The mixing and homogenization of the slurry are generally carried out mechanically using ball mixers (zirconia) and the viscosity is adjusted by adding a solvent. The slurry, under magnetic stirring, is then introduced into a casting mould with a pump.

Different techniques are used, depending on the thickness:

– casting by extraction (combined effect of the viscosity and gravity) for strip thickness ranging from 15 to 50 µm;

– casting by rolling (blade method) for thicknesses ranging from 50 µm to several mm.

Other parameters affect the thickness of the slurry, particularly the viscosity, the inclination of the casting tank and the surface tension of the slurry.

After drying and evaporation of the solvents, the ceramic tape is cut and then stacked. The plate is then thermo compressed. Finally, a heat treatment (a burning) is performed on ceramic plates to remove the organic substances before sintering.

5.8.2.3. *Sintering*

This heat treatment allows a system of individual particles or a porous body to move towards a state of maximum compactness (zero porosity). The material is heated below its melting temperature, leading to both a mechanical consolidation and to an increased density. The sintering is described as a succession of steps:

– slight withdrawal or slight swelling after the removal of the binder;

– internal reorganization of grains by creating bridges at the contact joints;

– start of junction part between the grains by creating bridges at the contact points;

– formation of a strong skeleton;

– elimination of open porosity between grains;

– elimination of closed porosities.

These phenomena are the result of various transport mechanisms (surface diffusion, at the grain boundaries and in the volume, phenomenon of evaporation, dissolution/crystallization, material transport to intergranular areas). A powder must have specific characteristics in order to optimize the sintering process such as high chemical purity, a tight distribution size, an isotropic *habitus*, small size and monodisperse particles.

The sintering cycle (rate of temperature change during heating and cooling, temperature and dwell-time duration nature of the atmosphere) must be adapted to each type of material.

5.8.2.4. *Metallization*

The electrical contacts are usually made of precious metals (Ag, Pd, Pt). The filing of electrodes may be produced by different methods (spraying, screen printing rolling or immersion in silver (*dipping*)). After removing the binders and solvents, the silver-based mixing diffuses superficially in the ceramics during a heat treatment carried out at a temperature between 500°C and 900°C, depending on the type of silver used. The firing cycle depends on the morphology of the particles of silver, the particle size, the surface of the ceramic, but also of the wettability and of the melting temperature.

5.8.3. *Technologies of ceramic capacitors*

In a uniform and homogenous field, the value of capacity, C, is given by:

$$C = \frac{\varepsilon_0 \varepsilon_r S}{e}$$

with ε_0, ε_r the permittivities of vacuum and of the ceramic material respectively, S the surface of electrodes and e dielectric thickness. An Increase of the capacity may therefore be obtained, from a geometric point of view by an increase of the specific surface of the electrodes and/or a low thickness and/or from a material point of view by using a high permittivity material.

Therefore several structures of ceramic capacitors exist, which are based on different parameters such as the final value of capacity, the dielectric strength and the degree of miniaturization.

5.8.3.1. *Structures of ceramic capacitors*

Two main structures are available.

5.8.3.1.1. Disk

This is the simplest structure. A single ceramic whose thickness can reach several hundreds of microns is achieved in the form of a disk. The electrodes are usually made of silver.

5.8.3.1.2. Multilayers

This structure applies to the different types of materials used. The goal is to artificially increase the surface with successive layers of metal and dielectric, leading us to consider that elemetary capacitors are in parallel (Figure 5.25).

The thickness and number of dielectric layers vary, depending on the value of the capacity and from one manufacturer to another. Capacity values between 1 pF and 1 µF are likely to be reached.

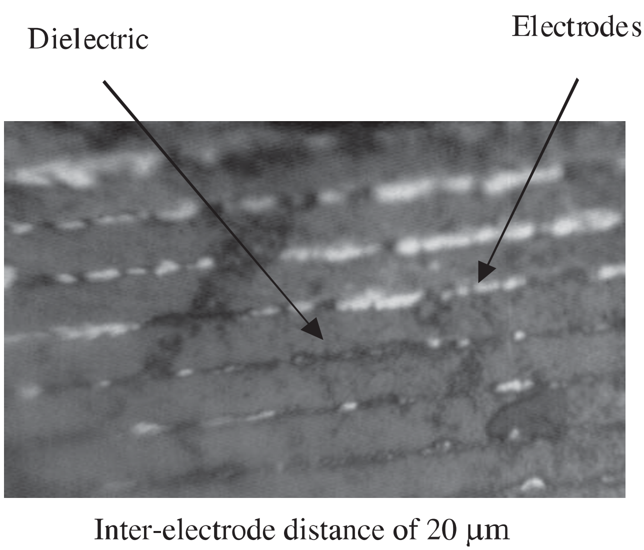

Figure 5.25. *SEM picture of a multilayer structure*

The external contacts are made of metal endings that are welded on to connections. The component is then encapsulated in a resin. It finally leads to a component whose volume is several mm^3. The capacity per volume unit of such components is very large.

5.8.3.2. *Electrodes*

5.8.3.2.1. Nature

Electrodes are one of the key issues in the manufacture of ceramic capacitors. The metals used are generally precious metals (Ag, Pd, Pt, etc.), or indium, gallium, and/or their eutectic and/or their alloys.

These electrodes are connected at their ends by two endings, which may be of two types. These endings are Ag/Pd (which is an expensive option) or nickel/tin (Ni/Sn). These endings are diffusion barriers to limit the spread of lead solder in the dielectric, which would result in the deterioration of the component properties (Figure 5.26).

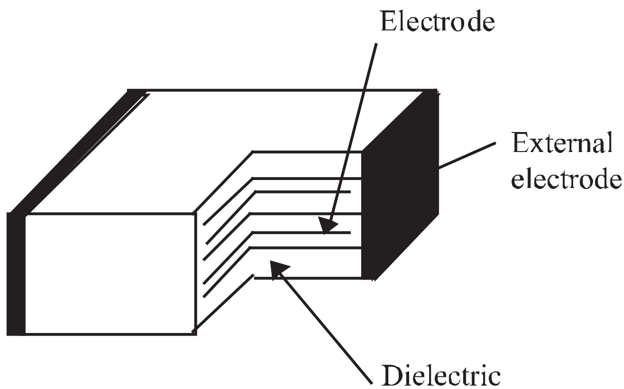

Figure 5.26. *Scheme of a multilayer capacitor*

5.8.3.2.2. Electrical properties of electrodes

The resistivity of metals and the thickness of electrodes may have very significant drawbacks. Hence the high frequency losses are mainly associated with the series resistance of the capacitors, which itself depends on the resistance of electrodes. This resistance is often increased by skin effect. For the frequencies where this effect is negligible, and for the multilayer structure presented, the share of losses attributable to the electrodes is:

$$2\pi \nu R_s C \approx 4\pi \nu (\frac{\rho_e}{e_e})(\frac{a}{b})$$

with: a, the length over which the electrodes are superimposed, b, the width of the electrodes, and e_e, ρ_e, respectively their thickness and resistivity.

This approximation leads to dielectric losses at 1 MHz of about 2 10^{-2} for a capacity of 50 nF with Pd electrodes ($\rho e = 10^{-7}$ $\Omega \cdot$m) of 3 μm thickness .

For higher frequency applications (> 100 MHz), losses are controlled by the skin effect and the metal that is used for the electrodes must be less resistive.

Finally, note that the metal/dielectric contact must be as close as possible to avoid the formation of an interface leading to the existence of a stray capacitance whose role will be even more damaging the higher the value of the ceramic permittivity. As an example, if the ratio of permittivities between the metal oxide layer and the dielectric material is about 1,000, the ratio of thicknesses in the case of a multilayer structure must be at least 10^{-5} to be considered as negligible. A thickness of 25 μm for the dielectric material therefore lead to layers whose dimensions must be less than the nm to be regarded as negligible. This simple example illustrates the importance of careful manufacturing of this type of structure.

5.8.4. *The different types of components*

5.8.4.1. *Definitions*

The distinction and definitions given below are nothing but subjective. However, it is usual to find them. There are three types of ceramic capacitors, which differ in their electrical properties.

5.8.4.1.1. Type I components

Their capacitance ranges from 1 pF to 1 μF. They have low dielectric constants (6-500) that almost never vary, especially versus temperature. More exactly, their temperature coefficient can be positive, negative or zero, but must have a low value. These capacitors also have a constant permittivity versus both the voltage and the frequency. They are mainly used in the high frequency range. Their dielectric losses are very low (tgδ < 0.01).

5.8.4.1.2. Type II components

The capacitance of these components ranges typically from 2.5 pF to 0.4 μF. The dielectrics are generally ferroelectric ceramics like barium titanate. Many doping materials may be introduced to ensure a nearly constant value of the capacitance versus the temperature and to obtain a high permittivity (a few thousand). However, this value is changing with many parameters such as the applied voltage, temperature and frequency, etc.

5.8.4.1.3. Type III components

The range of capacities of this type of ceramics is from 33 nF to 1 μF. The large permittivities (of the order of hundreds of thousands) are due to the grain/grain boundary structure of these ceramics. Their use is in applications requiring low losses, high insulation resistance but which do not demand a stability of the capacitance value with the voltage, the frequency or the temperature. Finally, their breakdown voltage (due to their "real" thicknesses) is relatively low, in fact preventing their use for "high voltage" power electronics.

5.8.4.2. *Capacitors of type I: materials and applications*

Ceramics with permittivity less than 10 such as porcelain (zirconia or steatite), refractory based-cordierite, aluminum silicate, aluminum nitride, are mostly used in insulation functions. They are used in so called DCB (direct copper bonding) substrates, high voltage insulators, spark plugs, etc. As capacitors, their applications are in the field of high frequencies (up to and beyond GHz). Their properties must be particularly controlled: low dielectric losses, constant ε with temperature and frequency, etc. For permittivities above 10, the main applications of these materials are capacitors used in electronic circuits and known as NPZ (negative, positive or zero variation of their CTC). In addition to appropriate temperature dependence, they have low losses.

The materials used are:

– Glass: (silicate, with lead, borosilicate, alumino-silicate, etc.) with various percentages of Si, Na, K, Ca, Mg, Al, etc., conferring dielectric permittivity between 3.8 and 15 and CTC between 40 and 600×10^{-6} /K. The interest of this type of capacitor is, on the one hand, its low dissipation factor (10^{-4}), low dependence of its properties with frequency and, on the other hand, to its insensitivity to temperature and humidity.

– Ceramic-based glass: they involve a glassy part and a crystalline part. Heat treatment gives them their structural properties. Since the crystalline part has permittivities larger than glass, it is necessary to control its dimensions. The latter sets the final value of the permittivity and, consequently, the capacity per volume unit of the component. It has to be remembered that it is possible to obtain multilayer capacitors based on tapes of lead glass, barium, strontium, nobiate, etc., whose properties will mainly depend on the grain size. Their permittivities vary between 200 and 1,200 at room temperature and can be very stable in both temperature and frequency. For the lowest grain sizes the thickness of these layers may vary between 20 and 200 µm.

– Porcelains: This term is used to describe a dielectric made from a mixture of glass and one or more crystalline phases but which does not use manufacturing techniques specific to ceramics. The best known are lead silicates. The layers used are in the order of 200 µm, their permittivity is about 15 with a good temperature stability and high resistivity (> 10^{14} Ω·cm).

– Mica is a mineral with splits whose thicknesses range from 50 µm and more. The ruby shape ($kAl^2(Si^3Al)O^{10}(OH)^2$) is the most widely type of mica used in electronics. Its permittivity varies between 5 and 9 and has a good temperature stability (10^{-5} to 10^{-4} /K) and a dissipation factor of a few percent. This material, because of its structure, is sensitive to pressure. Particular attention must be given, during coating or encapsulation, not to exert too much pressure, the changes of capacity with pressure being around 4×10^{-10} /Pa. Finally, being in the form of strata, mica is sensitive to moisture (which will have a tendency to bind interfaces). The components are of the multilayers type and connections are made by clamping.

5.8.4.3. *Capacitors of type II: materials and applications*

The components of type II are mainly based on ferroelectric materials, many of which have a perovskite structure type (ABO^3) or an ilmenite type of structure. In the first step, the definitions needed to understand this family of materials are reminded. Few examples are given and their behaviors are depicted. Their main properties are defined. These components are the most commonly used in power electronics because of their large capacity per volume unit, their non-linear behaviors with both the voltage and the temperature.

5.8.4.3.1. Definitions

As already reported (section 5.8.1.4), a ferroelectric material has a polarization Po even in the absence of electric field. In addition, the polarization P according to the applied electric field is neither linear nor reversible: the hysteresis loop. Figure 5.27 allows the definition of key values that are useful:

– Ps: spontaneous polarization, corresponding to the saturation value;

– Pr: remnant polarization, which is the value for a zero field;

– Ec: coercive field, corresponding to the field necessary to cancel the polarization.

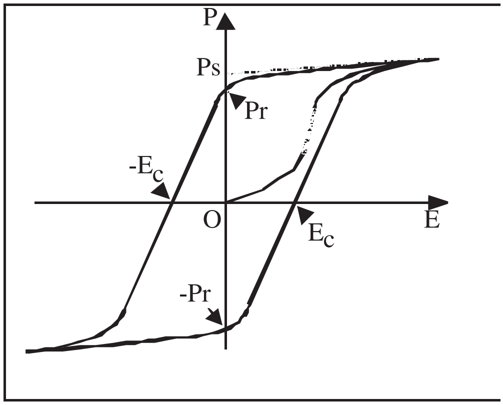

Figure 5.27. *Example of hysteresis cycle obtained in a ferroelectric material*

However, the ceramics used are not mono crystalline materials. As a consequence, the cycle shape is changed (Figure 5.28b).

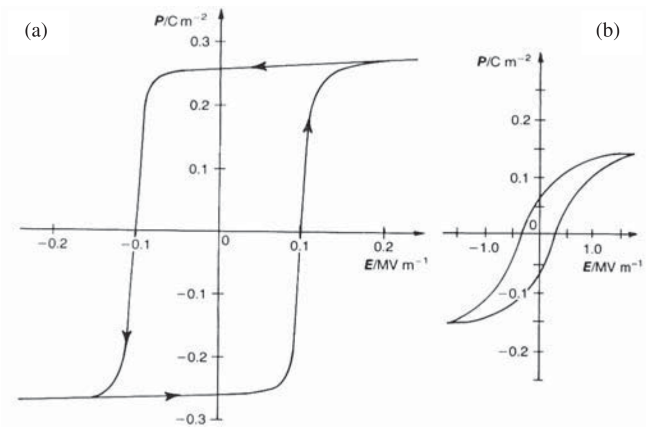

Figure 5.28. *Hysteresis cycle and orders of magnitude of major quantities in a sample of monocrystalline $BaTiO_3$ (a) and in a ceramic (b)*

If the material is heated beyond the so-called Curie temperature, the relationship P(E) becomes linear and the material becomes apolar: it is in its paraelectric state. Figures 5.29 and 5.30 respectively illustrate these behaviors in a crystal of barium titanate and in a commercial capacitor.

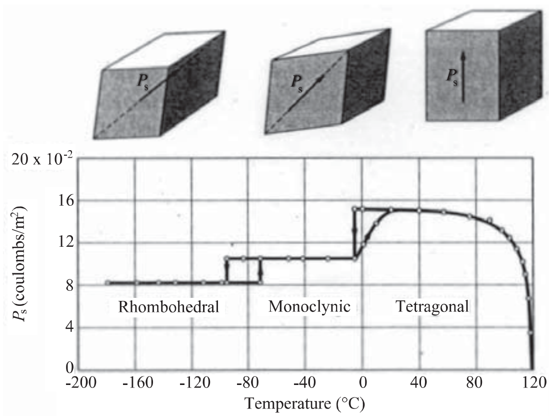

Figure 5.29 *Evolution of the permittivity in a monocrystalline $BaTiO_3$, as a function of temperature, along one of its axes*

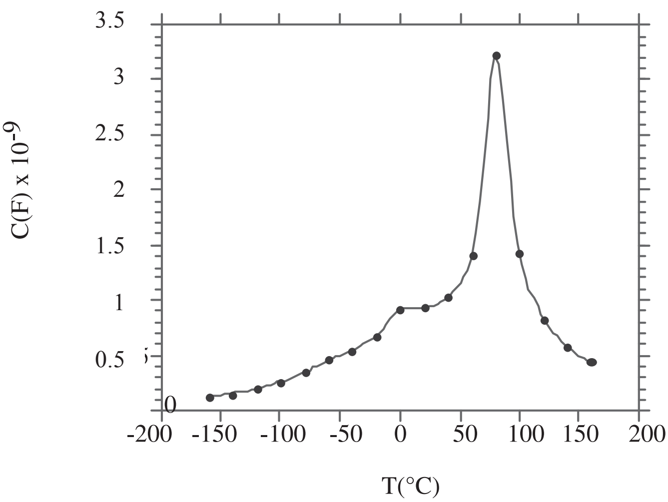

Figure 5.30. *Evolution of the capacity of a $BaTiO_3$ ceramic according to temperature*

5.8.4.3.2. Capacitors available on the market

These components are classified according to their properties by various standards such as EIA (*Electronic Industries Association*) and IEC (*International Electrotechnical Commission*). A code is allocated to them, such as Z5U for the EIA standard or 2F4 for the IEC standard. It allows us to specify the temperature range and changes in the capacitance of a capacitor over a given temperature range. This variation is expressed as a percentage of the value of the capacity measured at 25°C under a zero polarization field. Table 5.1 shows, for the EIA standard, the different codes.

EIA Code	Temperature Range (°C)	EIA Code	ΔC/C (%)
X7	–55 to +125	D	± 3.3
X5	–55 to +85	E	± 4.7
Y5	–30 to +85	F	± 7.5
Z5	+10 to +85	P	± 10
		R	± 15
		S	± 22
		T	+22 to –33
		U	+22 to –56
		V	+22 to –82

Table 5.1. *Codes according* to *EIA standard*

Generally, these standards are difficult to meet and the manufacturers prefer to give, in addition to a code, the electrical characteristics of their own components. Table 5.2 shows an example of electrical data supplied by manufacturers and where you can see the gap between the codes and the electrical characteristics may be seen.

Finally, nominal operation voltage of these components is given for a few tens of volts. In fact, their non-linear behavior with voltage (Figure 5.31), representing a disadvantage, generally prevents the manufacturer to ensure a stable capacity for use at higher voltage.

Type	Unom (V)	Variation (ΔC/C) (%)	Temperature Range (°C)
Z5U MB	50	± 20	+10 to +85
X7R MB	50	± 10	–55 to +125
Y5V MB	50	± 20	–30 to +85
BX	50	± 20	–55 to +125
2F4	100	–20 to +80	–25 to +85
Y5V MM	50	–30 to +80	–25 to +85

Table 5.2. *Manufacturer data for samples*

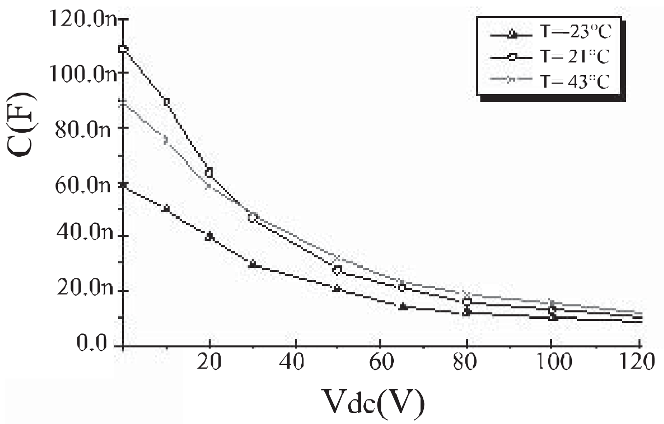

Figure 5.31. *Evolution of capacitance value with the voltage in a Z5U capacitor*

However, their use is possible for larger voltages (up to 10 times the rated voltage specified by the manufacturer). Also rarely reported is the variation of properties according to frequency (Figure 5.32).

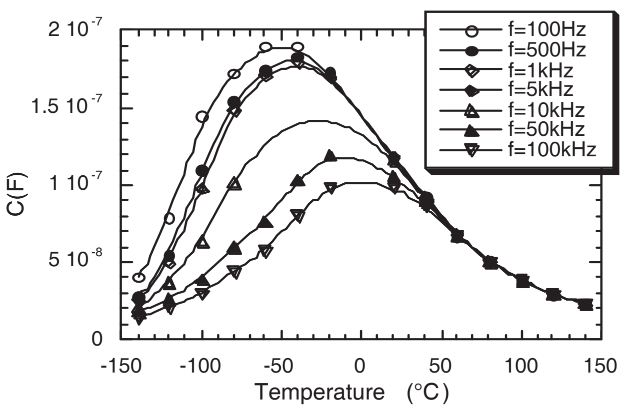

Figure 5.32. *Variation of capacity according to temperature and frequency*

Knowledge of these properties is generally sufficient to design the capacitor in its application.

5.8.4.4. *Type III capacitors: materials and applications*

Under certain conditons, preparations with barium titanate or strontium may exhibit permittivities higher than 100,000, but with high losses and low resistivities, which decrease with the voltage. Mastering the manufacturing process, coupled with an understanding of physical phenomena involved, lead us to obtain in a reproducible way this type of material, with, however, higher values of resistivities compatible with electronics applications. In order to understand their operation, the easiest way is to consider thin dielectric films with a large surface, obtained through the oxidation of the grains of barium titanates or strontium which were previously made conductive by adding appropriate doping (La3+, Ba2+, etc.). However, these structures do not behave at all like a resistor in series with a very high capacitance value. Indeed, these structures have very non-linear behavior of their current - voltage characteristics, which can be explained by the existence of a semi-conductive layer barrier. This behavior is related to the nonlinear resistivity of the grains with the applied voltage, which affects the amount of charge stored at the interfaces and therefore the capacity.

The most commonly encountered materials in the synthesis of such components are:

– for the ceramic phase: barium titanate or strontium;

– for the materials conferring conductivity to the grain: yttrium, lanthanum, niobium, antimony, etc.;

– for the additives: silica, alumina, etc.;

– for the electrodes: silver, indium/gallium, nickel/chrome, all chosen to avoid the formation of a Schottky barrier at the metal/ceramic interface.

These materials are very difficult to produce, thus explaining the rarity of their use.

These components can, because of their non-linear current/voltage characteristics (described by an equation of type $\mathbf{I = A\ V^n}$), be used as voltage clamps in power supply. Thus, by combining specific compositions based on barium titanate and strontium, dielectric permittivities ranging between 50,000 and 230,000 have been measured with values of non-linearity (n) of around 15! These components can operate up to 50 V.

5.8.5. *Summary – conclusion*

There is no doubt that ceramic components will take an increasingly important place in many applications, especially for applications involving large gradients of temperature and voltage. At a time when power components with high temperature features occur, it is obvious that ceramic materials will be the only ones likely to promote optimal operations.

Tables 5.3 and 5.4 summarize some of the most important materials mentioned.

Type	Capacity Range (µF)	DC voltage Range (Volts)	Tolerance on capacity (%)	Range of temperature (°C)
Ceramic (small ε) Disk and tube	1 pF–1.0	80–20K	+/–20	–55/+85
Ceramic (large ε) Disk	1 pF–1.0	80–20K	+/–20	–55/+125
Ceramic (small ε) Multilayer	2.5 pF–0.4	25–200	+/–20	–55/+85
Ceramic (large ε) Multilayer	0.033–1.0	3–30	–25+50	–55/+85
Ceramic Layer Barrier	1 pF–1.0	100–400	+/–5	–55/+100
Mica	0.01–4	200–15 K	+/–20	–55/+325
Reconstituted Mica	0.5 pF–0.01	300–500	+/–5	–55/+125
Glass	5 pF–0.004	300–500	+/–5	–40/+70

Table 5.3. *Summary of the main characteristics of the different materials presented*

Type	(ppm/°C)	Maximum Frequency (KHz)	tanδ (%) (1 kHz, 20°C)	tanδ (%) (1 MHz, 20°C)
Ceramic (low ε) Disk and tube	–5000 +100	10^6	< 0.01	0.1
Ceramic (large ε) Disk	–	10^4	1	4
Ceramic (low ε) Multilayer	+30	10^4	0.001	0.1
Ceramic (large ε) Multilayer	–	10^3	1	4
Ceramic Layer Barrier	10^3	1	1	5
Mica	+100	10^7	< 0.1	0.1
Reconstituted Mica	–	10^8	< 0.1	0.1
Glass	+1000	10^6	0.1	0.1

Table 5.4. *Summary of main characteristics of the different materials presented*

5.9. Specific applications of ceramic capacitors in power electronics

In addition to their high capacity per volume unit, the most interesting property of ceramic capacitors for power electronics is the non-linearity of their capacity with the applied voltage. Works have shown the interest of such non-linear ceramic capacitors in three main applications.

5.9.1. *Snubber circuits*

This application seems to be the most interesting because it can limit the switching time and the power that should be dissipated by the resistance of the snubber. Figure 5.33 gives the voltage across a semi-conductor in the particular case of a dissipative snubber. This figure enables a comparison of voltages in the case of linear and non-linear capacities (a) and secondly in the case of two non-linear capacitors (b).

The power dissipation is clearly even lower when the capacitor is non-linear. However, problems related to their withstanding voltage and temperature are likely to limit their use.

5.9.2. *In ZVS*

To reduce blocking losses of dual thyristors, capacitors are placed in parallel on the latter, thus reducing the area of switching operation. Using non-linear capacitors reduces the minimum current necessary for the switching of dual thyristors but also reduces the electromagnetic radiations.

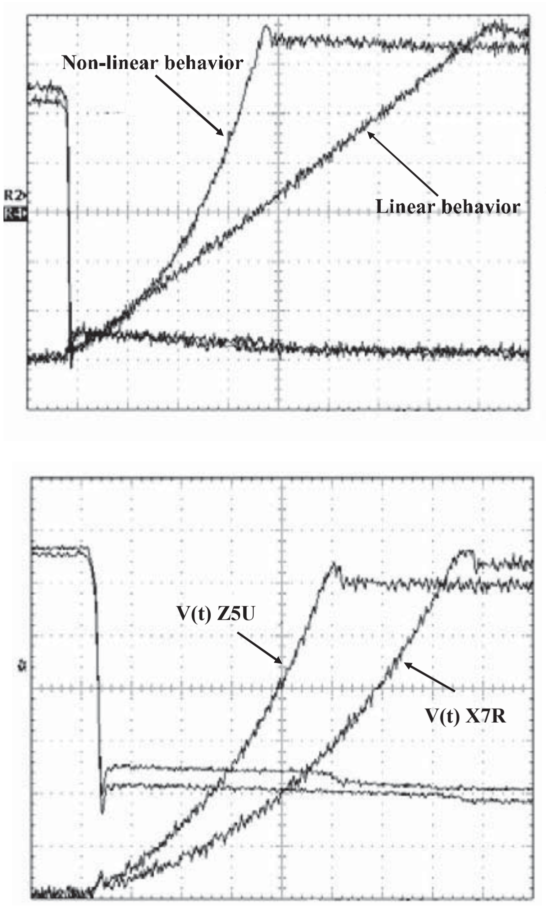

Figure 5.33. *Comparison of voltages for a linear snubber a) and a non-linear snubber b) for two types of non-linear capacitors*

5.9.3. *Series resonant converters*

In these structures, adjusting the power delivered to the load is performed using the switching frequency. The maximum power is given at a switching frequency equal to the frequency of the resonant circuit.

A small non-linearity of the capacitor can improve the dynamics of adjustment and may allow us, when the load is short circuited, to stop the operation of the converter for a backward phase shift operation ($F_d < F_0$) (Figure 5.34).

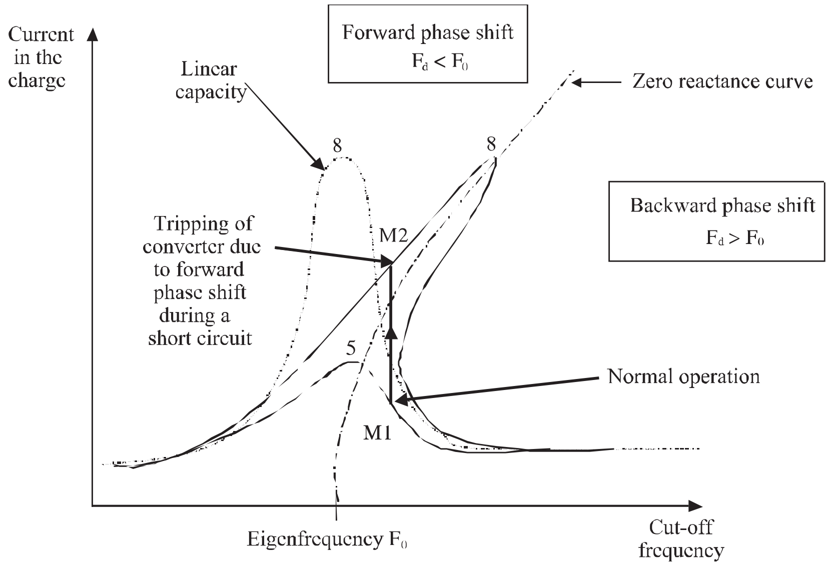

Figure 5.34. *Load current characteristics depending on the reduced frequency for two quality factors (5 or 8)*

5.10. R&D perspectives on capacitors for power electronics

5.10.1. *Film capacitors*

The capacitors made from polymer films (polypropylene, polyester, polystyrene, polycarbonate) currently represent between 25 and 40% of the capacitors available on the market. Due to their low permittivity (always <10), their specific capacity (i.e per unit volume) is low. The R&D focuses mainly on manufacturing processes allowing a decrease in thickness (<1 μm) in a reproducible manner while maintaining the main properties of these materials (reliability, high dielectric strength, low ESR and ESL, etc.).

Meanwhile, works are being carried out on optimizing metallizations (frames) in order to “protect” the component during breakdown or to ensure that the failure is always an open circuit.

Finally, new materials are being explored (polysulfone (PS), polyether etherketone (PEEK), polyetherimide (PEI)) which should enable use at temperatures up to 180, 230 and 300°C, respectively.

5.10.2. *Electrolytic capacitors*

The R&D works on aluminum-based electrolytic capacitors are to expand their area of operating voltage via an increase in the anode thickness, to make them more reliable via a monitoring of the electrolyte, and finally to find a replacement fluid with lower resistivities (polypyrol, polythiolen, etc.).

Regarding tantalum-based electrolytic capacitors, encapsulation, packaging, the search for a solution to their use in dry form, or the replacement of MnO_2 current frames by conductive polymers, or finally the development of new geometric structures with several anodes, are all key points in the process of exploration.

5.10.3. *Ceramic capacitors*

The efforts of R&D are currently mainly focused on materials, both dielectric and conductors. Regarding the dielectrics, research concerns the process of implementation to decrease thicknesses, mastering of specific properties (ferroelectricity and anti-ferroelectricity) and reduction of dielectric losses.

Many materials are already candidates whatever the manufacturing process (sol-gel, hydrothermal, thick layers, etc.). They are BT, PZT, SBT, PLZT, etc.

Frames are also subject to particular interest for at least two reasons: the cost of metals employed (noble) (Ag/Pd), and the method of disconnection in the case of failure which should be an open circuit type but is most often a short circuit.

Finally, note that most of these ceramics are particularly suited for integration because of their ease of implementation, their technological compatibility with semiconductors and their excellent thermal properties.

5.11. References

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