FIM TECHNOLOGY

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INTRODUCTION

For more than 30 years, energy storage capacitors have been designed according to the existing technologies used in filter capacitors. The dielectric, including insulating layers and impregnant have been mainly adapted to the specificities of discharge application conditions. This was particularly significant in the 90’s, during which a profound change of d.c. filter capacitor technology led to a new line of energy storage capacitors based on an all film design, which integrated all the knowledge acquired, not only in the d.c., but also in the a.c. field.

D.C. CAPACITOR EVOLUTION

In 1960, the usual design of d.c. filter capacitors for medium and high voltage, based on a mix of paper + aluminium foil impregnated with mineral oil, was improved when replacing the mineral by castor oil.

In 1970 when polypropylene film appeared, the dielectric was modified : the mixed dielectric (paper and film) was impregnated with a synthetic oil, but the energy density did not increase significantly. All-paper designs remain the reference in many large projects.

In the meantime, for voltages ranging from 900 volts up to 5000 volts, metallized paper is an interesting solution, especially in terms of controlled lifetime.

Used with one or two layers of paper, or with a polymer film, it has become the reference for filter and energy storage capacitor, mainly because the self-healing properties of the metallization.

During this long period, a lot of improvements have been carried out with respect to:

- the performance of paper (density increased up to 1.35 - number of weak points reduced)
- the edges of aluminium layers (laser cut to avoid sharp edges)
- the manufacturing process (better control of paper drying by measuring the depolymerisation index)

However two major points limit the performance of these capacitors:

- aluminium foil capacitors: no information can prevent against the breakdown and/or the short circuit
- metallized paper capacitors: the self-healing properties of metallized film capacitors induce large quantities of gases, which increase the internal pressure. Protective devices like pressure switches and/or disconnectors (for filter capacitors) try to limit the negative effect of the gas, but at the end of life, there is still a large amount of bulging on the sides of the can.

At the end of the 80’s, this situation was no longer acceptable for the traction field, using very large capacitors banks. It became necessary to create some fundamental changes in the capacitor design.

NEW REQUIREMENTS

For new traction projects, which started in 1990, new specifications appeared based on two keywords : safety and control.

The main criteria for the D.C. capacitors were :

- completely safe products (no explosion or catastrophic failure)
- capacitance control over the lifetime of the device
- no bulging of the can
- high power available
- reduced weight and volume
- high tolerance of peak discharge currents

Quite the same requirements appeared for energy storage capacitors devoted to electric guns and large laser projects.

A wide program of development was launched in 1989, with two main ideas:

- the dielectric must be a polymer
- the metallization must participate to a better use of the dielectric

THE NEW D.C. CAPACITOR

A choice of the most accurate combination of raw materials was made from a group of three polymers, three metallization types and eight impregnants. Considerations for this choice included chemical and physical test files, like compatibility between the components, and electrical tests including:

- 32 hours step stress tests to reach the dielectric limits
- long time (500 to 10000 hours) endurance tests at high temperature (70°C)
- Discharge tests to simulate faulty working conditions.

All these electrical tests were performed on industrial size windings or capacitors.

The best combination was an association of **polypropylene film**, **aluminium metallization** with reinforced edges and **rapeseed oil**.

Raw materials

The polypropylene film

This film met practically all the requirements needed by the D.C. capacitors.

- available thickness between 4 and 20 microns
- Surface roughness from 0.02 µ (smooth film) up to 2 µ (rough film also called hazy film)
- low number of conductive points : average of 0.4/ m² under 300 v/µ
- dielectric constant lower than hoped : 2.2
- high level of electrical breakdown. Fig 1 shows the minimum, maximum average breakdown values

depending on the thickness of the film for one manufacturer.

- high level of reliability and repetitivity of the film batches.

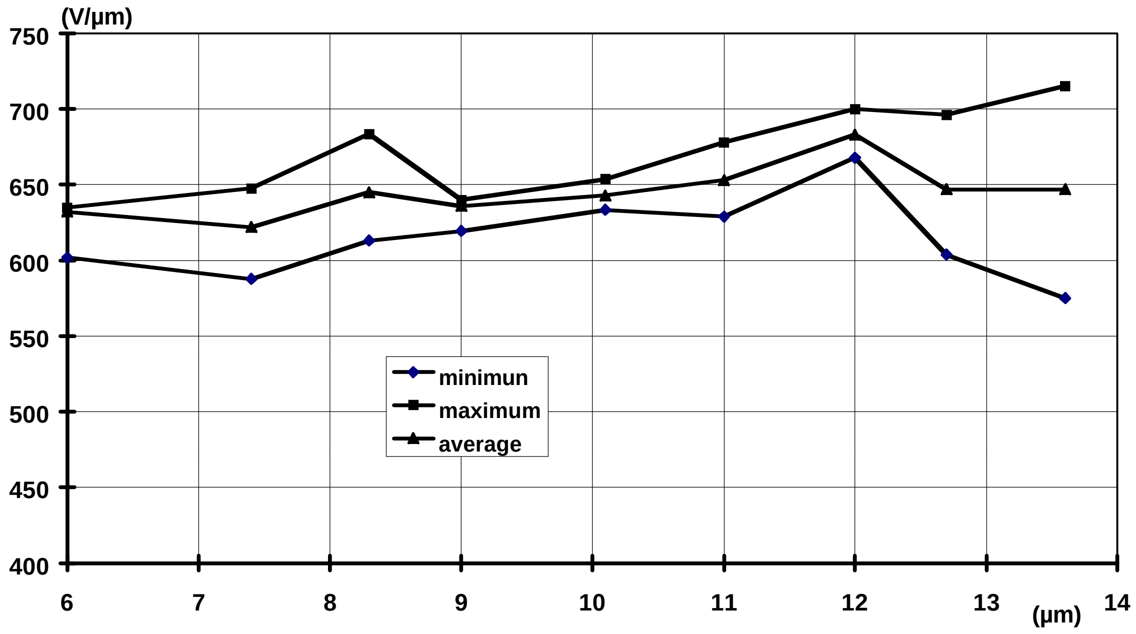
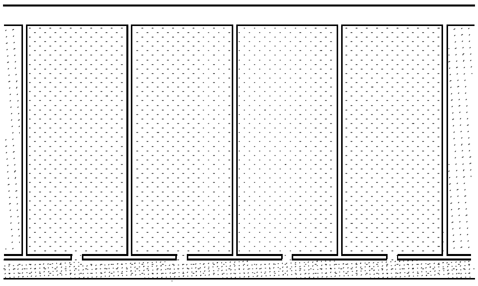


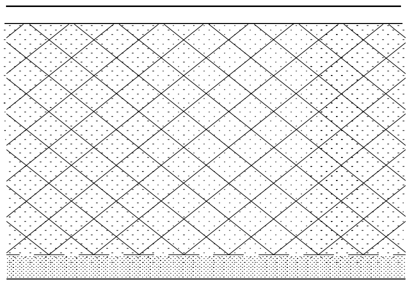
Fig 1 Dielectric strength on hazy polypropylen film vs thickness

Metallization

The metallization is the key to the self-healing process. It can be altered or adjusted in several ways in order to minimise this process, for instance, by surface segmentation or with various resistivities ,or multi-tracks designs which help increase the voltage of the winding.

When the surface is segmented (see drawing hereunder), generally fuses protect small areas. When a puncture occurs in one area, the fuse is blown out and the corresponding area is insulated , leading to a reduced capacitance loss.





Hereafter are summarised some results regarding the influence of segmentation over a 6 years period:

Year	1990	1992	1994	1996	2000
Segmentation	T	T	Mosaic	T	sprayed
Surface unit (cm^2)	42	42	1	28	0.00001
Fuse / unit	1	1	4	1	1
Stress	1	1.1	1.33	1.47	1.67
Volume	1	0.79	0.54	0.36	0.29
Weight	1.35	1.07	0.73	0.49	0.39

Without any segmentation, the goal is always to obtain a small demetallized area around the puncture of the film sufficient to withstand the applied voltage without any secondary effect on the closed layers, despite the surrounding energy.

The rape seed oil

In addition to the usual requirements, like reliability and homogeneity between batches, rape seed oil presents two main performances:

- Due to its low viscosity, it flows easily between the film layers during the filling operation. It impregnates the film, but only slightly because of its permachor value so that the swelling of the film does not exceed 2 to 2.5%.This avoids having any effect on the behaviour of the metallization on the film.
- High gassing property, probably one of the best among the impregnants, allows it to work under the worst conditions of partial discharges. The gas bubbles which occur at each shot (in case of surge voltage in the filter capacitor) are absorbed by the liquid.

In addition, its high flash point (250 °C) and fire point (300 °C) make it comparable to castor oil.

Properties of the capacitor

The initial requirements for safety have been fulfilled: no remaining short circuit. Only a drop in capacitance due to the fuse effect or the demetallized area is evident. At the end of filter capacitor life, the drop in capacitance is 2% (typical value) without any bulging of the can. For energy storage capacitors, this capacitance drop can reach 5% of the initial value, depending on the customer’s specifications.

Fig 2 shows a test result obtained when testing a 30 liters capacitor at 1.8 times its nominal voltage. At the end of the test, the whole capacitance is lost and the swelling of the can is limited to an acceptable width. With a capacitance lost of 2%, i.e. at the real end of life, no bulging occurs.

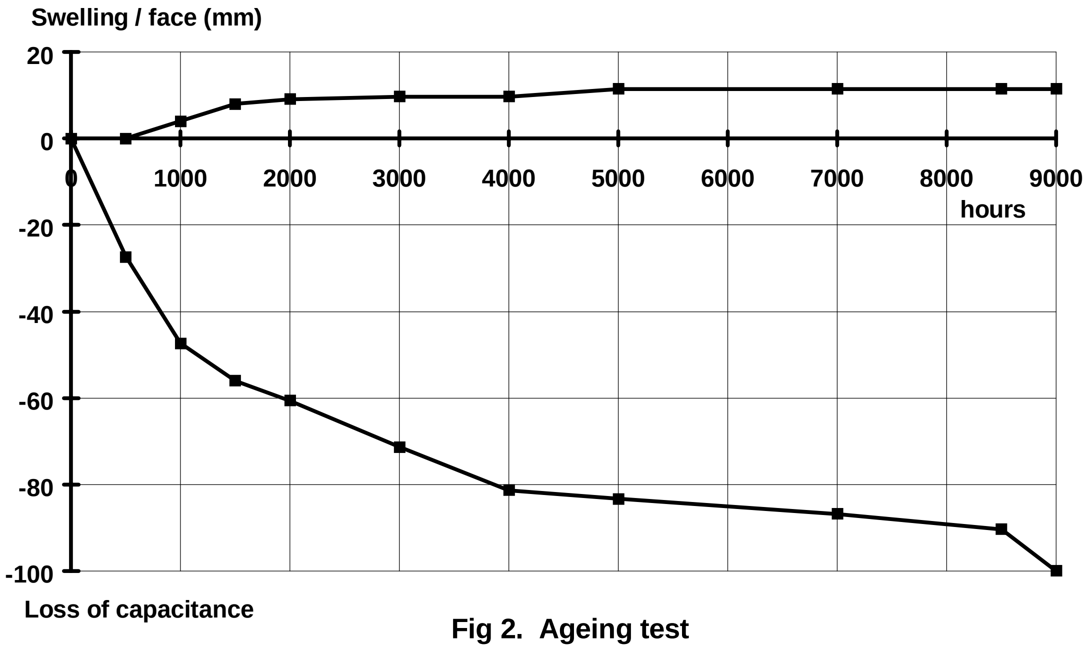


Fig 2. Ageing test

- volume and weight : compared to the 1990 situation, to date, volume in divided by 3.7 and the weight by 3.1.

These two large reductions are a result of the constant increase of the dielectric stress and the replacement of paper (density : 1.35) by polypropylene film density : 0.9). Consequently, the density of the capacitor drops from 1.65 down to 1.25.

Capacitance control

In most applications, capacitance control, operated according to the control plan of the user, can be used to indicate ageing of the component. This makes prediction of capacitor replacement possible because no failure is observed.

When a problem is detected, for example an unacceptable drop in capacitance or increase of loss factor., an analysis of the capacitor could reveal the reason for the observed deviation.

The capacitor in this case acts as a detector. If there is a large number of self-healing points and corresponding blown fuses, the capacitor is being subjected to unexpected high surge voltages.

If , there is a normal number of self-healings points and a large number of blown fuses, high currents are going through the capacitor.

If the contacts between metallization and metal spraying are crowded, surge currents exist in the loop where the capacitor is installed.

Experience

Over the ten last years, about 54 000 capacitors based on the above design have been operating in the field without any defects. The Mean Time Between Failure resulting from this experience is now more than 10,000 million hours.

TRANSFER TO ENERGY STORAGE

Because of the positive results presented by this technology and the high performance obtained in the short term endurance tests, a new development started in 1995.

The working parameters are totally different to those of filter applications. It is therefore necessary to study two main fields :

- behaviour of the dielectric under high stress
- influence of the reversal voltage, the hold time at full voltage, the charging time and the repetition rate

Dielectric stress

Even if the drop in capacitance is extended to 5% at the end of the life of the capacitor, the objective is to reduce the drop in individual capacitance to a minimum value.

The initial “T” segmentation pattern created a 42 cm² elementary capacitance surface. The mosaic solution is not completely adapted to large discharge currents.

To date, the solution is based on the association of two effects. The first one is the self-healing itself, which will complete its process once initiated. In case of trouble, a second level of safety is provided by the remaining fuses.

At first, the drop in capacitance is equivalent to some mm². The fuses then insulate some cm².

With this solution, the drop of capacitance is strongly reduced, placing it totally with a secured process.

Reversal voltage

As observed in the filter capacitor working under faulty conditions, mainly in case of an external short circuit, the reversal level leads to important modifications in the lifetime of the capacitor.

Fig 3 shows the results of tests performed on medium size capacitors which are subjected to a 1000 shots-per-step test. Between 10 and 90% reversal, the ratio of the volume for the same lifetime is about 2.

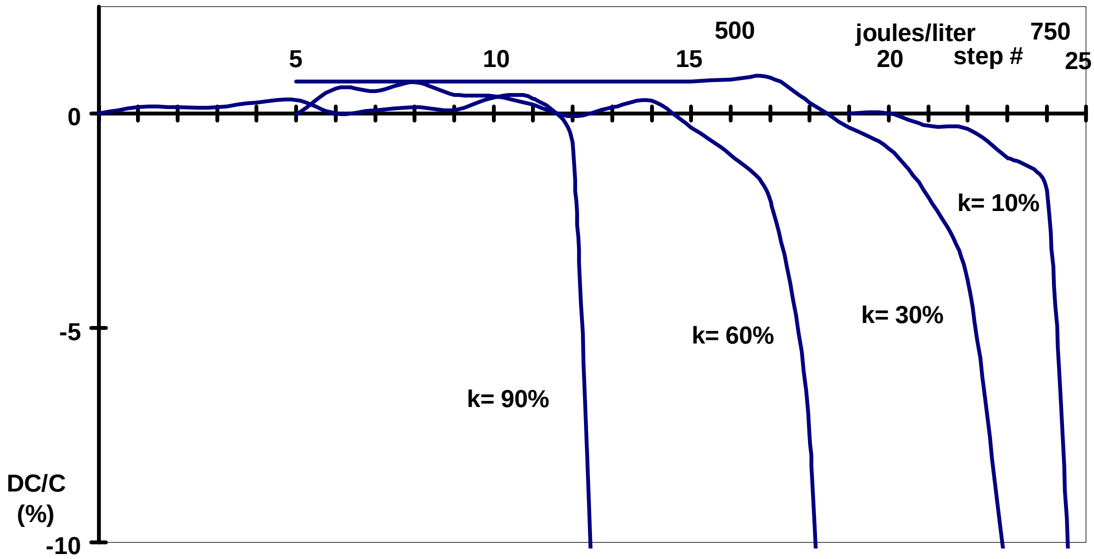


Fig 3. Capacitance drop vs 1000 shots/step

Thanks to the design of these units, the curves are very precise (the distribution is well centred), compared to those which are found in the paper/film/aluminium foil technologies.

Also, for high voltage reversal, the ageing of the capacitor becomes significant.

Fig. 4 shows a test result reached under the following conditions : 10 000 shots with a 10% voltage reversal, followed by 25 shots at 60% voltage reversal and again by 10,000shots under the initial conditions.

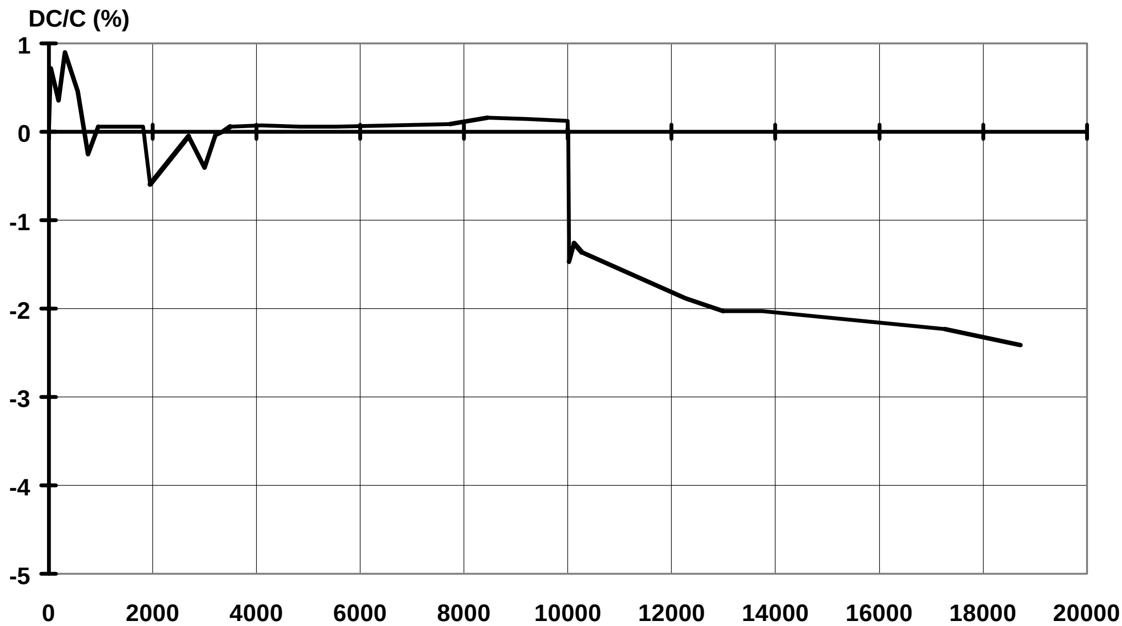


Fig 4 Capacitance vs # shots (10% reversal + 25 shots at 60%)

In the first period no change of the capacitance occurs. The next 25 shots lead to a significant, but controlled decrease of the capacitance (practically the same value per shot). In the last period the capacitance is decreasing slowly, because the film has aged after the 60% reversal voltage test.

CONCLUSIONS

The first objective: the safety characteristic of metallized (**M**) polypropylene film (**F**) impregnated (**I**) with rape seed oil (**FIM technology**), is reached. Due to technology improvement, we multiplied by 3 the energy density for D.C. filtering and now for energy storage field. The maintenance is light due to only capacitance and loss factor measurements. This technology is replacing the previous film foil capacitors.