# Cut and dried!

## A new dry capacitor for high-voltage DC applications

Birger Drugge, Martin Carlen, Sari Laihonen, Luc Spronck

**First units of a new generation of dry high-voltage capacitors developed especially for indoor DC applications are already in commercial operation and confirming their early promise. The new capacitors are smaller, store twice the energy in half the volume, and weigh 80% less than the fluid-impregnated units they are designed to replace.**

**The dry capacitors have a tubular polymer casing that defines the voltage per meter length, opening up a whole new area of application opportunities. By combining eco-efficiency with environmental friendliness, they embody ABB's strategy of using advanced technologies to provide more efficient and sustainable solutions for transmitting electrical energy.**

Visibly very different due to their much smaller size and cylindrical design, the new dry capacitors are already making their mark in commercial use, for example in the DC links of high-voltage DC (HVDC) installations, where they stabilize DC transmission voltages ranging from 9 kV to 150 kV.

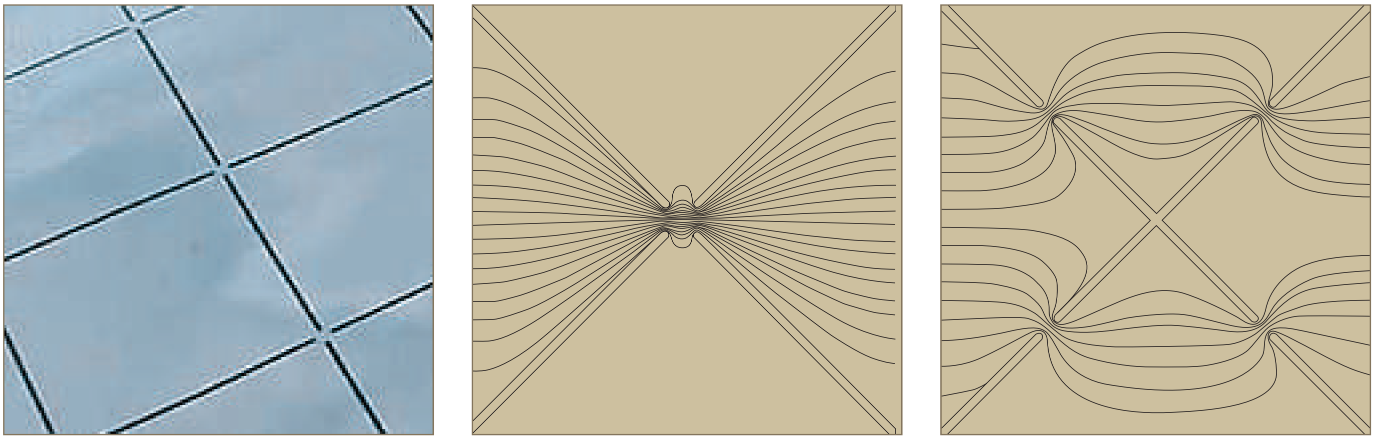
As with most innovations, the new capacitor technology builds on previous achievements as well as recent R&D work carried out to solve specific application-related problems. A look at how capacitors have developed from 'wet to dry' helps to explain the importance of the new technology.

The smaller, the better. ABB's new dry capacitor for high-voltage DC stores twice the energy in half the volume and weighs 80% less than a conventional capacitor of the same rating.

### Wet and dry – a brief history

Conventional high-voltage capacitors are made up of several capacitor elements connected internally in parallel

**1** Metalized capacitor film (left), showing typical segmentation. The size of the segments is about 1 $cm^2$. The electrical interconnections in the edges serve as fuse gates.
Finite element calculation of the current density for a corner connected (center) and mid-side connected (right) mosaic electrode pattern.



and in series, according to the capacitor's required electrical data. The capacitor elements comprise metal-foil electrodes separated by a dielectric made of polymer film impregnated with a special fluid. The assembly is housed in a metal enclosure, to which bushings are fitted for the electrical connections.

This technology has resulted in electrical field stress levels which can reach five to ten times the level in other types of high-voltage equipment. The electrical insulation of capacitors is therefore a key factor in their design and operation.

In the early 1990s, so-called metalized film technology was introduced in capacitors for 1-4 kV DC applications, for example in traction and industrial drive systems. The polymer films used here are basically the same, but the electrodes consist of a thin layer of metal deposited directly onto the film. These elements are also usually impregnated with oil or a similar insulating liquid.

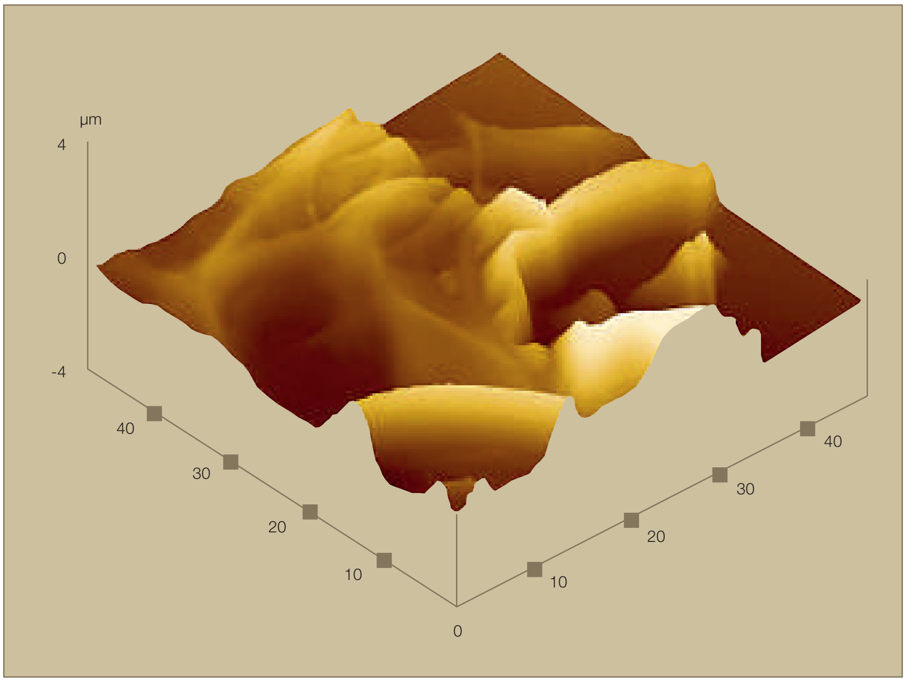
A few 'dry' concepts have, over the years, also been presented in which the capacitor container is filled with a gas instead of liquid. Since the early 1980s, too, low-voltage power capacitors with metalized film have appeared on the market that contain neither an impregnation liquid nor impregnation gas. ABB is the first company to apply the self-healing metalized film technology commonly used in low-voltage capacitors to high-voltage DC power capacitors.

### Why metalized electrodes?

Polymeric film capacitors with aluminum-foil electrodes exhibit a very large current-carrying capability. In the event of a dielectric breakdown, all the energy stored in the capacitor discharges into the fault. In large capacitors fuses are therefore connected in series with the individual elements to protect them from the high powers that can be discharged. Thus, if a fuse responds and disconnects an element, the capacitor can lose a few percent of its capacitance.

Metalized film capacitors employ a different principle for the power limitation. Resistance is introduced directly into the electrode by choosing an appropriate electrode conductivity. In addition, the electrode, with a thickness measured in nanometers, can be segmented and the individual segments interconnected by current gates to create a matrix of local fuses **1**. Should a breakdown occur, the metalized area and current gates around the fault vaporize to isolate it from the rest of the capacitor. This process is known as self-healing. Since only a very small part of the active area is destroyed, the loss of capacitance is negligible. In a large capacitor, many thousands of partial breakdowns would have to occur before a reduction in capacitance is noticed.

2 Surface of a polymer film, observed using atomic force microscopy




The increase in electrode resistance (as 'seen' by the load current) depends on the specific electrode pattern, and has to be taken into account in the design. 1 shows, as examples, the current distribution for two different electrode patterns, each resulting in a different value for the effective resistance.

Metalized film capacitors are capable of higher field strengths as a result of these characteristics.

### The development project

In 1998 a project group was formed and given the task of developing a dry high-voltage capacitor for use with ABB's new HVDC and SVC Light technologies. What was wanted was a dry capacitor with low inductance that could be installed close to the power semiconductors, which can then be more efficiently used. The capacitor was intended for use indoors, as the HVDC and SVC Light concepts require modules to be assembled and tested in the factory and then shipped to sites ready for use.

It was decided very early on in the project to use metalized film, partly because ABB Jumet had already been using it very successfully in its dry low-voltage power capacitors for two decades. Another factor was the extensive know-how ABB had accumulated in the manufacture of impregnated metalized film for 'wet' capacitors for traction and drive applications.

> Control of the self-healing phenomena is one of the keys to the new capacitor's outstanding performance.

### Testing the new technology

The new capacitor technology benefits from a broad knowledge base, built up over many years, as well as focused development work. ABB Corporate Research centers, in collaboration with the core business unit, have for years been carrying out basic research into the properties of polymer and dielectric polymer films. These properties included, among other things, self-healing and aging phenomena.

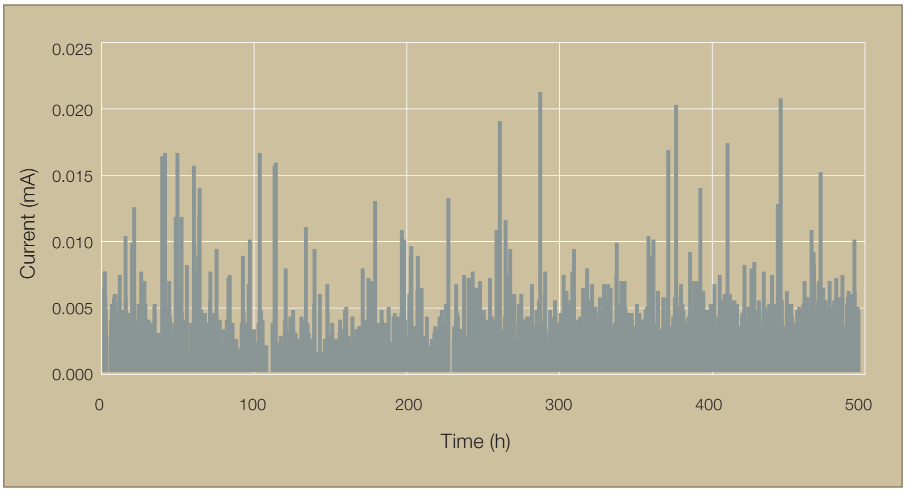
Being able to control the self-healing phenomena is one of the keys to the new capacitor's outstanding performance. It was made possible by a special, ABB-designed metalized film pattern as well as newly developed process technology. Simulation of the internal fault-clearing process, especially of the plasma dynamics, provided highly reliable data that were important for both the electrode pattern design and the subsequent manufacturing process.

ABB has its own automated test method for determining the electrical performance characteristics of dielectric films. In this method, different areas of the film are stressed using electrodes with varying surface areas until dielectric breakdown occurs. The breakdown measurements are repeated many times for each electrode, and the resulting data analyzed using Weibull statistics. This test method has been found to be very useful for defining and understanding aging and the dielectric breakdown mechanisms. Also studied were the chemical and physical characteristics of the polypropylene film, for example using atomic force microscopy (AFM) 2.

### Performance and life evaluation

The investigation of the fundamental phenomena yielded important information, and this was used in the capacitor's basic electrical design. However, ultimately it is the performance of the capacitor unit as a whole that matters, and this is much more complex. Special attention was therefore given to the testing of the complete unit. To obtain fast and precise information about the performance of metalized film capacitors, ABB developed the partial breakdown recharge current method (PBRCM). This allows individual partial breakdown events to be observed and gives a much

3 Measured recharge currents




## Benefits of the new dry high-voltage capacitor

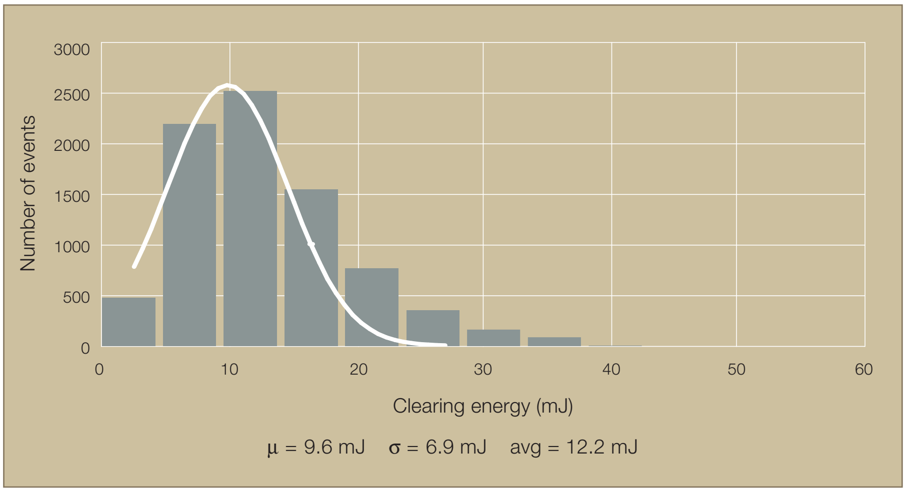
- High energy density, for a more compact design
- Low weight, for easier, also suspended, installation
- Polymer tube, acting both as housing and insulator/bushing
- Tube can be made longer for higher voltages – no need for racks and intermediate insulators as with conventional capacitors connected in series
- Can be mounted next to power semiconductors for low inductance
- No liquid impregnation fluids – does not spread fires
- Environmentally sound product – corrosion-free, does not need to be painted
- Allows seismic-resistant installations

better insight into what is actually happening in the capacitor. Traditionally, capacitor performance and lifetime are determined by means of accelerated aging experiments. The capacitor is stressed by a high electric field at high temperature, and the change in capacitance is observed. However, the test conditions have to be hugely exaggerated to obtain results within a reasonable time, and the effect of this can easily exceed what might be expected under normal operating conditions. PBRCM avoids this problem. The capacitors can be tested under more realistic stress conditions, and the results become available in a shorter time. The energy required to evaporate the electrode during a partial breakdown is determined by measuring the amplitudes of the recharging currents 3, 4. This information is an important input parameter for the electrode design. Since the energy, which should lie within certain limits, is strongly dependent on the voltage, an electrode conductivity has to be chosen that is appropriate for the specific voltage level.

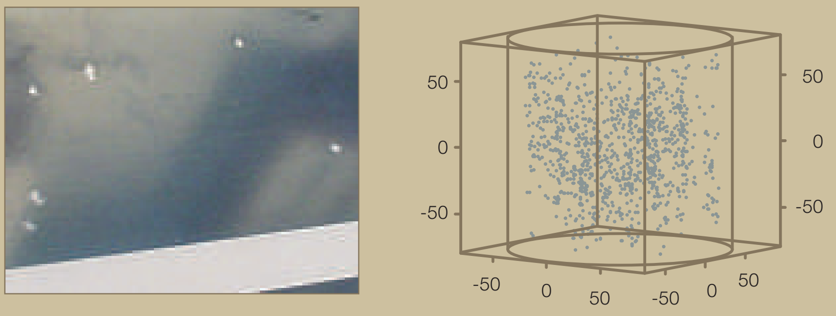
Examining old capacitor elements also provides important design information. ABB therefore developed an automated digital image processing system for analyzing damage caused to the metalized electrodes. Using this system, the number, size, and location of partial breakdowns in the capacitor windings can be determined. 5 shows a piece of metalized electrode that has been subjected to accelerated aging. The white areas mark the breakdown locations with vaporized metalization. They have a diameter of 1–2 mm. Statistical analysis of the results shows where the weak points in a winding are and where improvements are necessary. Correlation of the damage analysis statistics and PBRCM results provides further important input for the electrode design and manufacturing processes. Predicting polymer insulation lifetime is made much easier by the self-healing properties of the dielectric film.

> The capacitor can have elements added, in series, to obtain any desired voltage level.

4 Statistical distribution of the fault-clearing energy



5 Part of a metalized electrode (left) after accelerated aging, and a 3D representation of the breakdown locations in a capacitor element. The demetalized zones (white areas) insulate the breakdown channel from the rest of the electrode.




Usually, it is difficult to collect data on enough breakdowns to obtain a relevant statistical base for evaluation. But due to the self-healing properties, one test object can provide tens of thousands of breakdowns – each recorded with the temperature and electrical stress, plus the change in capacitance, leakage current and losses, as a function of time.

A life cycle assessment has shown the new dry capacitor to be environmentally superior to the conventional 'wet' type in every respect.

### Rounding it all off…

It was observed early on in the project that placing the capacitor in a polymer tube has several important advantages. Such a casing is cost-efficient and also light enough for the capacitor to be hung from rails fixed to the ceiling. And since the tube is made of an insulating material, the capacitor can have elements added, in series, to obtain any desired voltage level 6. This allows a significant cost saving, as the polymer tube acts as both housing and insulator/bushing, eliminating the need for the large insulators used to separate the series-connected capacitors in conventional rack installations. Providing the tube with a sufficiently thick wall also ensures good insulation between the capacitors and the walls of, for example, the valve enclosures in HVDC installations. Other advantages of using polymer are that it is corrosion-free and doesn't require painting.

The tubular casings that are used underwent exhaustive analysis and testing, as did the tube material itself. Among other things, these tests took into consideration the thermal expansion, pressure and mechanical forces that can be expected.

### An emphasis on sustainability

Sustainability aspects were considered at every stage of the project. A life cycle assessment (LCA) was used to calculate the environmental impact of each phase in the capacitor's life cycle, taking into account everything from the basic materials to the final disposal of the end product. Every aspect was audited and evaluated, including the extraction of raw materials, transportation, energy consumption, pollution levels, and lifetime benefits of the product, plus the energy and materials recovered and recycled at the end of its useful life 7.

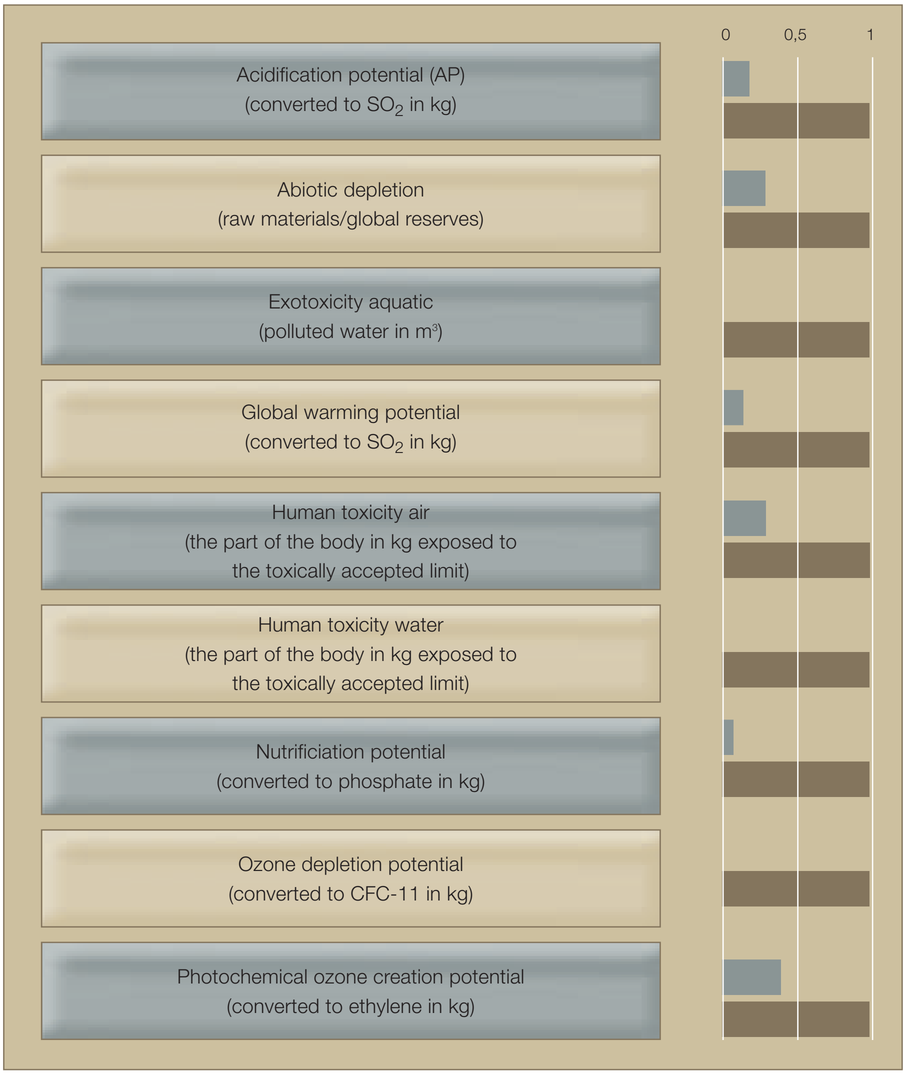
The environmental load indices on which the LCA was based use information from bodies and organizations with special databases containing sub-suppliers' data for processes, energy use, transport, and so on.

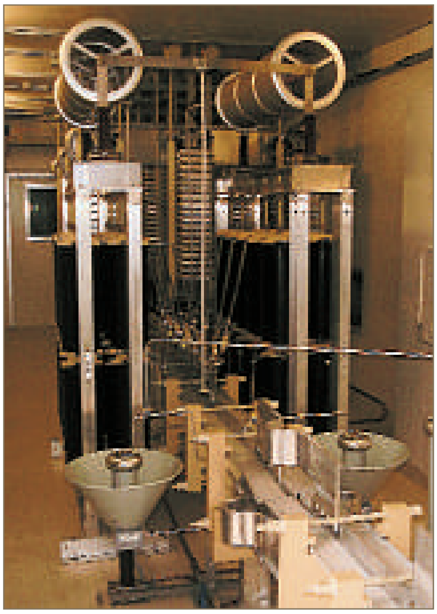
One of the manufacturing steps given special attention was the painting process. Conventional oil-impregnated capacitors have steel housings and these have to be properly protected against corrosion. They are therefore treated with a two-layer coat of special paint. During painting, solvents are emitted into the atmosphere and impact the environment. One development objective was therefore to exclude the painting process. This problem was solved by the choice of corrosion-free polymer for the tube housing.

An aspect that often dominates the total sustainability load index is the contribution made by the electrical losses over a product's lifetime. In the case of capacitors, these losses are generally very low. And since capacitors are installed

6 The voltage level of the new capacitor can be varied by adding elements in series.

7 Results of a life cycle assessment (LCA) comparing the conventional capacitor design with the new dry high-voltage capacitor for a specific application. In every case the new capacitor (top bar) is environmentally superior.



DC-link capacitor bank with the new dry HV capacitors, here in an HVDC Light converter module

to reduce losses in power systems, their net environmental load effect tends to be positive.

ABB used LCA to compare the new dry capacitor with the standard ‘wet’ type in an installation that requires the use of eight conventional capacitors, but only three dry capacitors on account of their better performance. Whichever aspect is considered, the comparison shows the new dry capacitor to be environmentally superior to the conventional design.

There are several reasons for this: the dry capacitor does without impregnation fluids, solvents, paints or other hazardous chemicals; less energy is required to manufacture and transport it; its losses in operation are low; and at the end of its useful life, it can be incinerated with a high return on energy.

## Going commercial

The first new dry capacitors went into commercial operation in summer 2000 in an HVDC Light installation[1] from ABB. The capacitors have operated reliably and without problems since day one.

The new capacitors are also being used in a 330-MW HVDC Light installation with DC transmission voltage of 150 kV that went into operation recently in the USA. A single dry capacitor, two meters long, is able to handle this high voltage.


**Birger Drugge**
ABB Capacitors
birger.drugge@se.abb.com

**Martin Carlen**
**Sari Laihonen**
ABB Corporate Research
martin.carlen@ch.abb.com
sari.laihonen@se.abb.com

**Luc Spronck**
ABB Jumet
luc.spronck@be.abb.com


[1] In an HVDC light installation, high-voltage capacitors are used in the DC link, where they stabilize the DC transmission voltage. HVDC Light is based on voltage source converters using turn-on/turn-off IGBT power semiconductors. This allows independent control of both the active and reactive power, and the same converter can be used as an SVC (static var compensator).