Siemens Matsushita Components

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# Dry MKK capacitors for modern rail traction

Power capacitors for DC link circuit converters are key components of asynchronous three-phase drives, which are now a world standard in rail traction. New manufacturing techniques have enhanced their performance while making them environmentally friendlier.

Non-self-healing film capacitors in rectangular cases or self-healing metalized paper capacitors, mainly housed in cans, (**Fig. 1**) were used in the first traction converters. Introduction of an oil-impregnated polypropylene dielectric marked the first step toward making power capacitors lighter and more compact. Further savings in weight and volume resulted from the gas-impregnated metalized film (MKK) DC capacitor in a rectangular case. Over the past 30 years, power capacitors for rail traction have been miniaturized by a factor of ten altogether. But there are no new low-cost dielectrics on the horizon that promise further significant reductions in weight or volume. So the only way to make these capacitors smaller is to make more efficient use of the film material available. The properties of unprocessed polypropylene film, for example, have been significantly improved by using an optimized granulate manufacturing process in conjunction with better matching of treatment processes.

## Gas impregnation superior to oil

The MKK DC capacitor is self-healing, has a structured metalization layer on the dielectric, is gas-impregnated, dry and environmentally friendly. It meets the requirements of IEC 1071 in full. The new design provides considerable practical advantages over oil-impregnated capacitors (**Table 1**).

Metalization is the key process in the manufacture and operation of self-healing capacitors. In the event of a puncture, the thin metalization layer vaporizes, so that a ring-shaped isolation region is formed around the puncture channel (**Fig. 2**). In dielectrics made of organic material, successful self-healing of the puncture depends not only on the energy released, but also on the quantity of carbon deposited in the isolation regions. This quantity is affected mainly by the thickness of the metalization layer, the material composition of the dielectric and the static pressure at the puncture point. Ongoing development has led to metalization layers containing alloys of zinc and aluminum, or with additional layers, e.g. of silver. These innovations have done much to stabilize the capacitance drift behavior.

## Structured metalization improves self-healing

Back in the 30s, it was found that that the failure rates of capacitors could be reduced by connecting a large number of partial capacitors in parallel and via fused links. But structured metalization was extremely difficult to implement on an industrial scale, so

**Table 1 The new MKK DC capacitors have numerous advantages over oil-impregnated types**

| Requirements | Properties | Benefits |
|---|---|---|
| Service life | $t_{BD\ (DB)}$ >100,000 h | High operational reliability |
| Capacitance stability | Insensitive to leaks | Operating life >5000 h even with serious leaks |
| Pulse-handling capability | $i/l$ >1.0 A/cm | Safe at short-circuit discharge |
| Pulse-handling capability vs. time | Consistently high values | Safe at overload |
| Loss factor | $\tan\delta < 10 \times 10^{-4}$ | Low thermal stress |
| Loss factor vs. time | Consistently low values | Increased useful life |
| Failure rate vs. time | Stable parameters | Consistently low failure rate |
| Inductance | <40 nH obtained | Suitable for IGBT and GTO power converters |
| Flame retardation | Gas impregnation | Low inflammability, suitable for subways |
| Contact assembly | Rugged plastic feedthroughs | Failure-free contact assembly |
| Weight | Lighter for comparable utilization | Benefits in operation |
| Environmental friendliness | Gas impregnation, no oil | Ease of disposal |

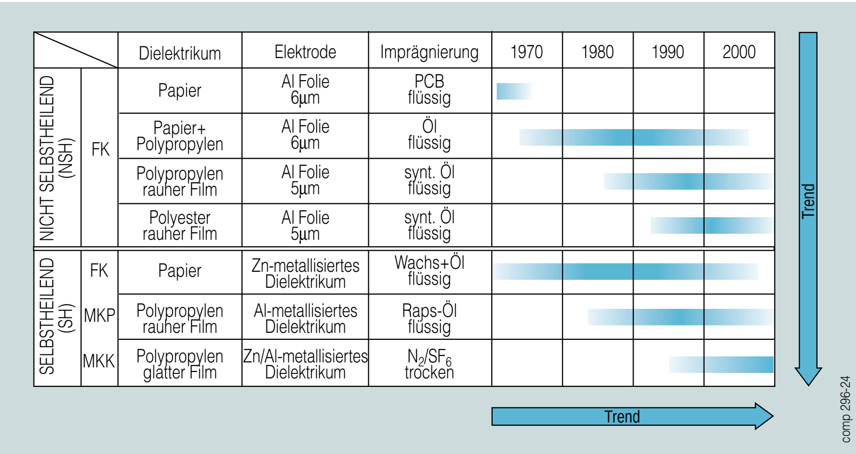



**Fig. 1 In capacitors for rail traction, the trend is moving away from non-self-healing to self-healing designs and from liquid to gas impregnation**

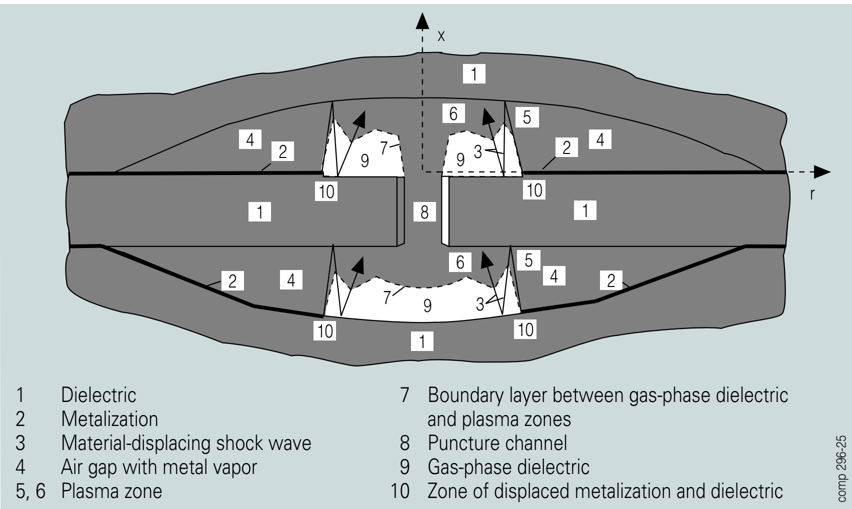



**Fig. 2 Self-healing puncture in a dielectric of organic material**

almost 50 years passed before it could be used in capacitor manufacture.

The structure of the metalization, which consists of partial capacitor and fuse geometry, must be adapted to the capacitor's thermal and electrical load. The energy released in a typical regeneration puncture is crucial to optimization of the structure. In a self-healing plastic film capacitor, it depends closely on the voltage under otherwise comparable boundary conditions:

$E^{SD} \infty V_{SD}^{4.7}$

where $E_{SD}$ is the energy released during the self-healing puncture in Ws, and

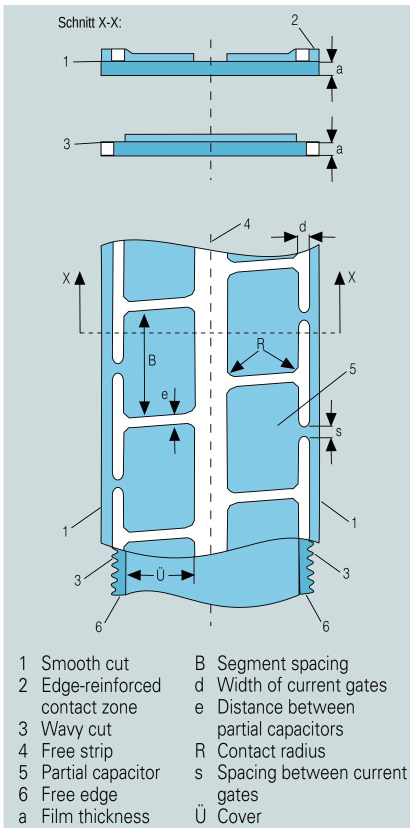
$V_{SD}$ is the voltage at the self-healing puncture in V.

For this reason, the fuse geometries and partial capacitor dimensions must be specially matched to ensure optimum film utilization. The degree of optimization of different structural layouts or film structures is determined by means of a step test which examines the dimensioning characteristic $V_{max}$ = f (d$C/C$ = 1%) and the regeneration behavior at various temperatures. This test loads the capacitor or winding by a voltage rise rate of, say, 100 V DC/min. The best step-test results were obtained with a dry film structure for an internal series connection, a segment structure manufactured in an offset metalization process, more than two fuses and distinct connection radii at the corner points of the structure surfaces (**Fig. 3**). In a direct comparison, oil-impregnated variants showed less favorable results (due to the roughness of the film which is essential to this type of impregnation).

## Combined wavy/smooth cut increases contact surface

Low-inductance link circuit batteries for IGBT (insulated gate bipolar transistor) converters make particularly high demands on the surge current stability of the capacitor. This parameter depends on the effective contact surface available. A combined wavy/smooth cut in conjunction with a defined small offset (to avoid the dangerous constriction effect at the film edges of plastic windings) triples the contact surface in comparison with previous designs. The current-carrying capacity of the contacts and the fuse constrictions is determined by means of surge discharge tests using 1000 pulses at each load stage (**Fig. 4**).

**Fig. 3 Film structure for internal series circuit with structured metalization**



| Maximum voltage load $v_s$ | Maximum load time per day $t_s$ |
|---|---|
| 1.10 × $V_N$ | 5400 s |
| 1.15 × $V_N$ | 1200 s |
| 1.20 × $V_N$ | 300 s |
| 1.30 × $V_N$ | 60 s |
| 1.50 × $V_N$ | 0.1 s |

**Table 2 Permissible overvoltage and load duration at a hot-spot temperature of 70 °C**

| Protective component | Property |
|---|---|
| Gas impregnation | Very low risk of bursting |
| Zn/Al-metalized winding structure | Very good self-healing capability |
| Structured metalization with offset process | High voltage strength |
| Integrated winding protection | Good overload capability |
| Stainless-steel casing with high deformability | Pressure stable >15 bar |
| Overpressure diaphragm | Low-cost protection |
| Overpressure switch* | Optional or additional |
| Overpressure disconnector* | On request only |

* Not standard

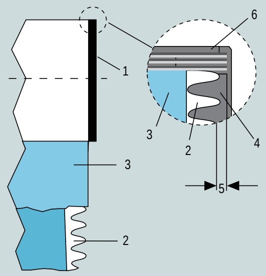
**Table 3 Multiple redundancy protects the MKK DC capacitors**

## Gas impregnation prolongs service life

Gas impregnation ensures that the service life of the MKK winding stack cannot be reduced by the effects of oxygen from the air. So even in the extremely unlikely event of a link circuit capacitor being punctured during operation, full functioning of the capacitor bank affected is guaranteed for more than 5000 hours. This has been verified by endurance tests lasting more than 10,000 hours at 70 °C on capacitors with a punctured ceramic feedthrough and on open winding stacks (without any protective can) in a controlled temperature cabinet at 70 °C for 1000 hours and with subsequent temperature variation (from –25 to +70 °C in a twelve-hour cycle at 1.25 × $V_N$) for up to 3500 hours.

## Constant loss factor in endurance tests

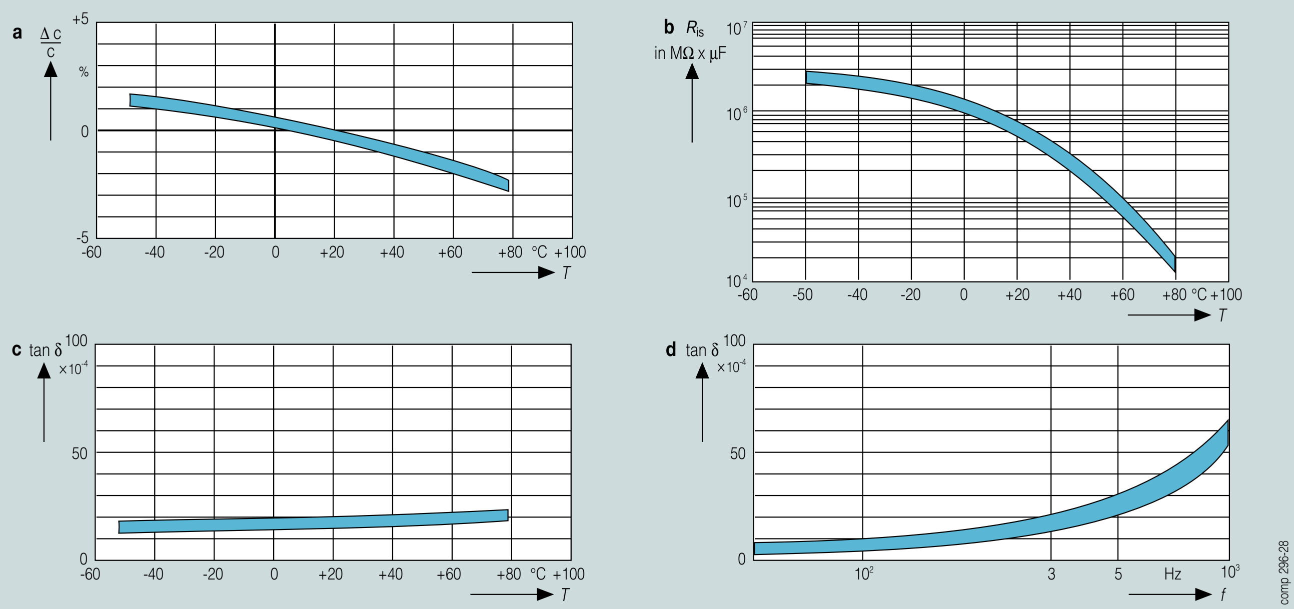
The curves in **Fig. 5** and the data in **Table 2** show the good technological properties of the gas-impregnated MKK DC capacitor. It is particularly striking that the loss factor remains largely constant over time after endurance tests, with a typical value of 1.25 to 1.40 × $E_N$. In addition, the strong tan δ rise (peel or crack effect) generated by the swelling of an oil-impregnated and metalized polypropylene dielectric can be avoided in principle.




1 Metal-spraying process with low thermal load on contact zone
2 Free edge with wavy cut
3 Zn/Al-metalization with edge reinforcement
4 Large effective contact surface
5 Small offset
6 Offset without constriction effect

**Fig. 4 Combined wavy and smooth cuts increase the contact surface of MKK capacitors**

**Fig. 5 Gas-impregnated MKK capacitors offer technological benefits over oil-impregnated MKP types: capacitance change (a) and insulation resistance (b) as a function of temperature, loss factor as a function of temperature (c) and frequency (d)**



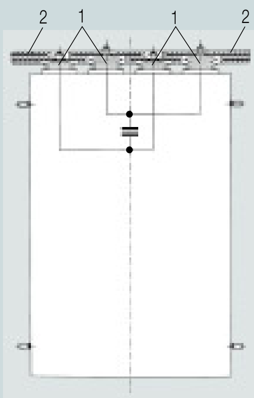
The capacitor consists of two flat winding stacks joined by conductive strips and plastic shells to form a fully insulated unit housed in a rectangular casing of stainless steel. Each flat winding is provided with two autonomous contact points by specially shaped conductive strips, each of which can sustain the rated current. The winding stack is electrically isolated by a new type of double-shell polypropylene insulation even at the corners of the casing, which are difficult to handle with conventional multi-layer insulation. But these plastic shells have other functions. They ensure that the winding packet is centered with the correct spacing with respect to the casing and maintain sufficient mechanical pressure between the winding and the inner wall of the casing. This design reduces the thermal resistance of the capacitor. As liquid impregnation is no longer used, the environmental and flame-retarding properties of the component are improved.

The new plastic feedthrough developed (**Fig. 6**) allows longer creepage or air paths and greater resilience to assembly forces than is the case with ceramic feedthroughs. The capacitor is protected by a fuse system with multiple redundancy (**Table 1**).

**Low self-inductance**

Three-phase drives for very high outputs are operated with phase modules. Although the symmetrical circuitry of the GTO (gate turn-off) with its particularly low losses can manage without low-inductance storage capacitors, the link circuit bank must be designed for very low inductance in comparison with asymmetrical circuitry. The switch in technology from metalized paper to dry MKK DC capacitors allowed the number of capacitors per bank to be more than halved, so that the self-inductance had to be reduced by the same amount. But the total circuit inductance between the semiconductor module and the link circuit capacitor is crucial to proper operation of the power converter. Development of power converter drives up to the megawatt range is currently being fueled by IGBTs. The low-inductance components must be connected as far as possible without additional leakage inductances. A stripline is recommended for connecting the capacitors (**Fig. 7**).

In the design of the MKK DC capacitor, care has been taken to implement a comparatively low self-inductance of around 400 nH. The new plastic feedthrough allows further reduction of self-inductance because the external terminal configuration (usually a stripline) can be attached straight to the contact level of the feedthrough. Versions with four terminals per capacitor and special design measures in the winding stack circuitry have self-inductances of about 35 to 50 nH per capacitor. By connecting a capacitor bank containing two low-inductance link-circuit capacitors, for example, via a stripline, circuit inductances of less than 100 nH can be obtained.




1 Optimized feedthrough
2 Fully insulated stripline

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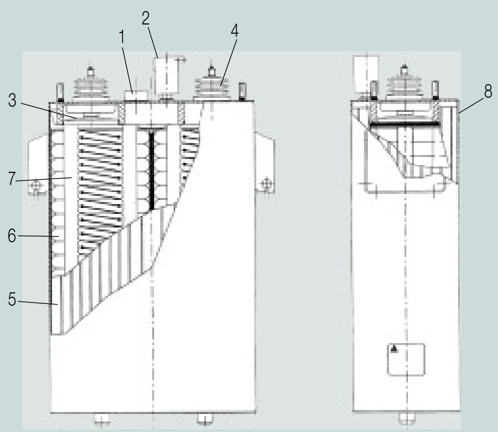
**Fig. 7 Optimum connection of a low-inductance MKK capacitor by a fully insulated stripline**

The demands of drive technology for extremely low inductance, savings in weight and cost, and environmental friendliness will in future dominate power capacitor design. Now that introduction of structured metalization has led to greater utilization of the dielectric, development resources must focus on winding technology as well as on further improvement of metalization structures. The flat winding used in the MKK DC capacitor has now ousted the round winding. Stacked film technology promises further increases in the operational reliability and permissible field strength of power capacitors for modern rail traction. ☐

**Fig. 6 The new plastic feedthrough developed allows longer creepage or air paths**




1 Overpressure diaphragm
2 Overpressure switch
3 Overpressure disconnector
4 Plastic feedthrough
5 Insulation shell
6 Flat winding stack
7 Stripline
8 Casing

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