Film Capacitors for DC Link Applications

The DC link of advanced frequency converters requires well adapted capacitor solutions. Traditionally, the segment of small and medium power converters <100kW has been exclusively served with electrolytic capacitors, while polypropylene film capacitors have been used for the high power range. Due to the improvements achieved in the performance of basic material, as well as optimised metallisation and winding processes, nowadays film capacitors are a possible alternative for a broad range of DC link circuits in the voltage range of 350 to >6500VDC. **Jens Luthin, Product Marketing Manager Power Capacitors, EPCOS AG, Munich, Germany**

Decisive for the decision to either use electrolytic or film capacitors are factors like maximum DC link voltage, applicable current and frequency spectrum, ambient temperature, requirements for low inductance, low losses and compact design. While electrolytic capacitors possess low specific costs per capacity, film capacitors represent an attractive option if high currents are applied and long life expectancies are decisive. Besides classical industrial converter applications, film capacitor solutions are designed for medical devices and will find a broad application field in automotive electrical and hybrid electrical propulsion. Figure 1 gives an overview of power capacitor concepts.

Film capacitor technology

Film capacitors for DC link applications today are manufactured based on windings made of bipolar oriented polypropylene film (BOPP). The recent development of ultra thin films (<3.5µm) is opening the voltage range down to 350VDC. These kinds of films are typically metallised with aluminium (Al) or a zinc- aluminium (Zn/Al) alloy. A fundamental safety mechanism all metallised film capacitors are possessing is the so-called self-healing property (Figure 2).

Impurities of the PP film are annealed by

Figure 1: Overview of power capacitor concepts

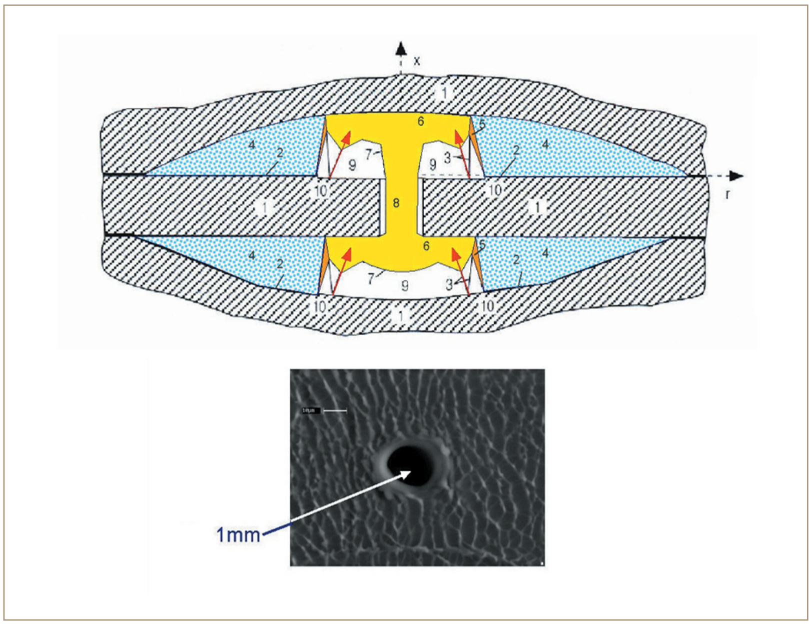

Figure 2: Self-healing property of film capacitors

creating small arcs resulting in little holes in the PP film surrounded by insulating conglomeration of residual material. Special metallisation profiles might be generated depending on the load conditions specified for the capacitor solution desired. The metallisation can be done with a segmentation pattern, including a fuse structure to master heavy load conditions. The connection of the electrodes is provided by a zinc layer sprayed onto the winding contact areas. Based on the desired mechanical concept and the electrical parameters required, three basic types of windings are available: round, flat or stacked (Figure 3).

Besides the sensitive process conditions of winding and drying, the basic means of impregnation used for film capacitors are gas, oil and different types of resin. Overload conditions are usually creating an extended number of self-healing events and lead to the creation of gases. Fully encapsulated film capacitors can be equipped with over-pressure disconnector constructions or pressure switches to improve safety conditions. Overload scenarios applied to film capacitors mostly lead to an open circuit condition, while electrolytic capacitors mainly fail by causing a short circuit.

Specification range of film capacitors

The specification range for DC link film capacitors is a multi-dimensional room (Figure 4). Besides nominal voltage, capacity and maximum current several other parameters may influence the design of a film capacitor. During the specification of a film capacitor, it is advisable to closely investigate the true voltage load including ripple voltage, repetitive voltage peaks, as well as rarely occurring surge voltages.

The voltage is determined by the thickness of the PP film used for the capacitor. State of the art design rules consider a field strength of approximately 150 to 250V/µm film thickness depending on the further design parameters. Design target is to implement the minimum film thickness that can be tolerated in order to reduce space consumption and optimise the utilisation of material.

Specifying the capacity (C), it is worthwhile to consider the minimum allowable capacity value needed for the application, including the decrease of capacity throughout the lifetime of the component ($\Delta C/C$). Compared to electrolytic capacitors which usually lose about 10% of the initial capacity or more, film capacitors are typically designed not to loose more than 3% capacity during the lifetime expected. IEC conform type tests using certain conditions for accelerated aging are applied to simulate and confirm the drop of capacity. In advanced and fast switching IGBT converters especially, the DC link current frequency spectrum must be well considered during the layout of the film capacitor. The main switching frequency, as well as high frequency fractions in the frequency spectrum, can cause strong heating of the capacitor, and if the switching frequency of the system is too close to the resonant frequency of the DC link, an internal busbar set-up is needed to avoid overloading the component. The aging process of a film capacitor can be approximated by a first order chemical reaction and may be described with an Arrhenius equation [1]. Basically, the electrical field strength combined with the temperature of the capacitor are the driving factors for the aging process. While the field strength is

Figure 3: Different types of polypropylene windings

defined through the voltage applied on a certain film thickness, the temperature inside the capacitor results from the losses (mainly dielectric and ohmic losses) [2] causing a temperature rise in excess to the ambient temperature.

It is very important not to exceed the hot spot temperature of the capacitor which would lead to structural changes in the PP film material which are reducing the expected lifetime. For standard designs, the typical hot spot temperature is around 85°C. If film capacitors shall be subjected to very high ambient temperatures, derating rules for the field strength need to be applied. In order to achieve highly integrated converter designs with advanced power density especially in automotive the requested temperature range goes up to about 125°C [3]. Besides the temperature aspects, the geometric requirements including the terminal configuration can also be a design driving factor deciding over the choice of winding style [4].

Classification of electrolytic compared to film capacitors

As a main factor for the classification of DC link capacitors, the voltage level is decisive. The voltage level below 450VDC is clearly dominated by electrolytic capacitors and is expected to remain the domain of this technology for long. The exception are the automotive applications (starting at approximately 350VDC) requiring the most compact designs with ultra low inductance, high current capability and operation temperatures significantly >100° C.

To achieve more than 500VDC, electrolytic capacitors need to be put in series connection, whereas film capacitors can be adjusted to different voltage levels by using small steps of different PP film thicknesses. Today, film capacitors for classical DC link applications are used up to 6500VDC. Below 100µF standard DC film capacitors in stacked or wound technology are used. Up to 900VDC, we talk about the low power range of power capacitors and around 20mF can be realised in one individual capacitor housing. Components with >900 VDC are usually called high power capacitors [5].

A further classifying aspect can be the terminal design. Electrolytic capacitors are equipped with snap in or screw terminals while film capacitors may be designed with a broad variety of alternative options. Small size film capacitors posses soldering pins or fast in connectors. On the high power side screw terminals are used. Apart from the standard options, special low power capacitors are designed with various flat blade type connectors, internal thread solutions up to busbar like configurations. In that range, the need for ultra-low inductance is apparent.

A third classifying aspect can be the encapsulation concept. Electrolytic capacitors usually have phenol resin top discs, aluminium cases and a shrinkage tube surface. Some film capacitor designs use a similar case concept with nylon or epoxy top discs. Typically, film capacitors are manufactured with plastic boxes or cases and furthermore with aluminium, steel or fibre enforced plastic housing. Depending on the impregnation concept, one facet of a capacitor can only be covered with a polyurethane or epoxy resin surface. In some applications with limited load, environments with low humidity, or in case the component is implemented in a sealed housing, it is favourable to use a non encapsulated naked capacitor design (Figure 1).

Application related design aspects

Several aspects to be considered for the design of DC link capacitors have already been named. From the application side, various additional factors should be considered. The load conditions for the capacitor can be either of a very dynamic nature; for example to be found in cranes, elevators or industrial equipment with cyclic load; or the operation is more like a constant, slowly or seldom changing load, for example in propulsion, transportation or pump drives. In case an energy reserve is needed to adjust to a dynamic changing load requirement, the DC link must be installed with more capacity. In high temperature environments, a compromise between the loss characteristics and the life expectancy should be found to optimise the capacitor design to the true specification conditions.

Critical temperature profiles and load cycles have to be closely analysed and even simulated to ensure the suitability of certain capacitor solutions. Life expectancy is the central element of capacitor design. The layout has to be designed to achieve the expected lifetime under the specified conditions. In power electronics capacitors are usually designed to remain unchanged throughout the entire life of the end device. In some applications, the maintenance and exchange of components can lead to enormous extra costs. For example converter driven wind power systems used in an off shore wind park should have the lowest achievable maintenance level and it is advisable to avoid the exchange of capacitors. To adjust to a critical very low volume availability, capacitor concepts using stacked or flat windings must be evaluated.

Based on the philosophy of the converter design, either modular set-ups or system integration has to be considered. In cases where the DC link of a certain converter design shall be adapted, for example, to different power stages, discrete capacity steps should be defined, being able to build up various DC link banks with a limited number of capacitor units. In cases where a project will use only one capacity rating, an integrable, optimised and technically well adjusted single capacitor layout is the preferable solution.

Quality is a major concern in various applications. Comparing the costs of different DC link capacitor options, not only the price per capacity should be considered, but a system cost analysis

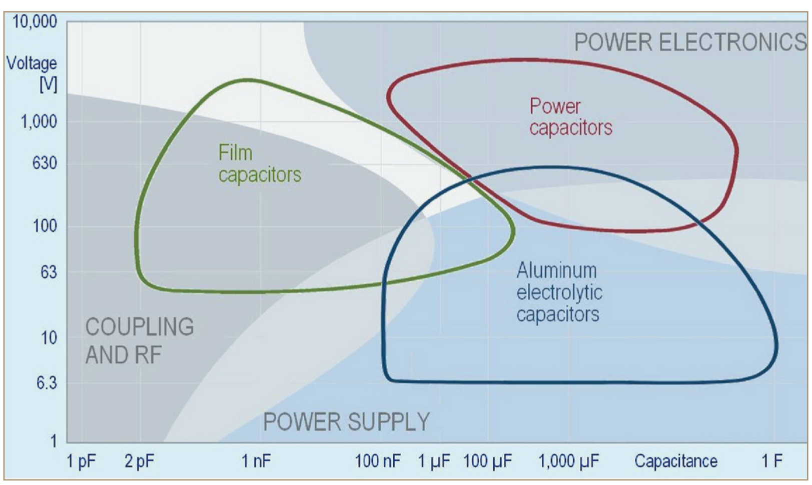

Figure 4: **Specification range of power capacitors**

should be made, including mounting requirements and labour time, busbar configuration, secondary materials and expectable maintenance requirements. Quality is a major concern in many aspects. In case an x-ray system equipped with a poor DC link capacitor solution is failing during operation, the consequences might be of very critical nature. If high power converters are built, solid encapsulation and safety mechanisms are advisable, as malfunction under overload conditions can have severe consequences considering the high energy stored in the component. Lifetime requirements shall be well adapted to the true requirement. The mission profile of an automobile converter is revealing that maximum capacitor load is only applied for a very limited amount of time. The overall life cycle of a car only seldom exceeds 12000 hours and the average current load is rather low. Consequently, highly integrated capacitor designs used at elevated temperatures can be designed close to the technological limits [4].

Guideline for the choice of DC link capacitors

In the past, certain specification ranges were determined by specific technologies and standard components. With the wider use of variable frequency converters, the increasing number of different concepts and technological approaches, and also the range of different Power Capacitors used is opening up.

In general, the fast development in converter technology, mainly driven by improvements of the semiconductors and the advanced software solutions, is impacting the business of capacitors as passive components. While, some years back, the specific capacity in a DC Link solution was about 100µF/kW, nowadays modern converter designs can work with 10µF/kW and in research projects it has been shown that this value can be further significantly reduced. For the capacitor manufacturer, that trend is accompanied with the request of integration and higher specific load.

It is not easy to apply a simple schematic in order to decide which kind of capacitor technology is the optimum one for a specific DC Link solution, but some easy rules can be applied: In many cases, the design driving factor for a DC link bank with electrolytic capacitors is the current. If it is possible to reduce the capacity to 30 to 50% and to apply an integration concept with optimised electrical and mechanical connection, a power capacitor could be an adequate solution at a comparable cost base. Decisive for the future success of power capacitors in small and medium size DC link circuits will also be the further progress in reduction of series resistance (R_s) and consequently losses. Typical R_s values are 1,5mΩ but with heavy duty designs today 0,5mΩ can be reached. Besides the rough general rule, many individual factors such as extra long life expectancy, exceptional mechanical requirements, elimination of hazardous materials, ultra low inductance, system integration, weight reduction could also influence the decision as to which capacitor technology should be implemented.

Conclusion

The DC Link application will gain importance for capacitor manufacturers. The market of converters and drives is growing in the magnitude of 10% per year and the demand for DC link solutions is increasing related to that, but it must be considered that the specific capacity inside the DC Link circuits is shrinking. At the same time, the technical requirements for the capacitors are increasing and the different applications require a highly diversified range of solutions. Consequently, adequate attention has to be allocated to the different specification ranges to properly adapt the progress in electrolytic and film capacitor development to the needs of the market coming up with innovative solutions.

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