Capacitors in Electric Drive Applications
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Abstract
This application reviews the technologies available for power systems in hybrid and electric drive vehicles. Included will be a matching of performance requirements with capacitor capabilities to optimize the selections for both operation and cost. Applications will center on converter and inverter circuits with the main emphasis on film and aluminum electrolytic capacitors and the performance issues that separate any preference between these two. Circuit parameters including ripple current, voltage and frequency as well as environmental concerns and extremes impacting performance will be highlighted. We will also emphasize projected life expectancies for both and how the applications will factor that.

Capacitor Requirements
As a preliminary to discussions of optimal performance characteristics for the best capacitor solution, a couple of points need to be defined as given. The capacitor must be capable of functioning over a long life. Considered to be the absolute minimum endurance is 10 years or 100,000 hours of operation. For the most part, most capacitors can achieve this endurance mark quite easily, but the harsh environments and electrical stresses encountered in many of the applications can be highly debilitating. The cabin environment requires a temperature range from -40°C to +85°C, while under the hood environments are easily up to 125°C, and some applications require 150°C, 180°C, and 200°C exposures. Contributing to the harsh environment are shock and vibration requirements. Special considerations in packaging and materials may reduce the performance capability but extend the life time capability of the device under these conditions.

The performance capability within the desired frequency spectrum must meet minimum requirements throughout the expected life of the component. The failure mechanism of the capacitor must also be considered along a spectrum from a desirable self-healing capability, to a less desirable gradual decay in performance, to an undesirable instant catastrophic and violent failure mechanism.

Above all of these considerations is cost. Regardless of the large improvements in performance, if this improvement is cost prohibitive handicapped to nominally acceptable performance, the cheaper solution will win out.

Capacitor Functions
In the drive system, there are three distinct functions demanded of capacitors: filtering (1), snubber functions (2), and the “DC Link” or power decoupling functions (3). As detailed in Figure 1, the AC power source is created by the alternator function that is converted to DC for battery storage. Common mode and differential mode filtering may be required to eliminate EMI/RFI noise from emanating from this part of the power system. The drive motors require an AC conversion from the battery and this is usually accomplished with IGBT circuits creating two or three phase AC voltages. The pulse currents at the input are extremely high and a large decoupling capacitor with extremely low ESR is desirable as a decoupling capacitor across the battery and the initial phase of these currents are sourced by the capacitor. The frequency component is complex as not only a fundamental frequency is created, but harmonics of
that fundamental exist and need to be compensated. Because the currents are extremely high and the IGBT are turned off in the midst of these currents, snubber capacitors are required across each switch element to absorb the energy of the collapsing inductive fields created during the high current flows. The voltages created in these applications are usually short duration but very high in magnitude.

**System Overview:**

![System Diagram]

**Typical Capacitor Types Used:**

- **1. AC Harmonic Filter**
- **2. Snubber**
- **3. DC Link**

*Figure 1: Power delivery system in automotive electric drive.*

**Filtering (EMI/RFI)**

In this application the impedance between 10 kHz and 10 MHz are most important. Noise generated in this spectrum can be suppressed by having an impedance magnitude lower than the load impedance. In many cases the solution involves the addition of one capacitor for each line, but there are cases where multiple capacitors of different values may be used to create a broader band filter.

A common solution for this application is with ceramic capacitors, but be careful in using this type of capacitor in lower frequencies; as these capacitors are nearly “perfect” in high frequencies (>=100 kHz), they may be very problematic in low frequencies (<30 kHz). They have a piezoelectric characteristic as well as an AC voltage coefficient that could create problems.

For low frequency applications, film and aluminum-electrolytic capacitors perform extremely well. The film will have lower parasitics of ESR and have greater voltage capability but the aluminum-electrolytic are less expensive. If the EMI problems are in the higher frequencies (>100 kHz), than ceramic and film may be the solution. In Figure 2, the impedance (Z) and ESR are plotted for a surface mount ceramic and film capacitor. These are both SMD devices and their impedances are very close. The low frequency ESR of the film is consistently lower than that of the ceramic. Adding leads on to the device will cause the ESR to increase a little but the ESL will increase significantly. The additional ESL will cause the device to have self-resonance (minimum Z) at a lower frequency and the impedance above that point will
be greater than that shown for the surface mount device. The inductance will be a concern for the higher frequency regions of the spectrum.

![Figure 2: Plot of Z and ESR(R) versus frequency for 1 μF, SMD, 50 volt film and ceramic capacitors.](image)

**Snubber Application**

![Diagram](image)

*Figure 3: Snubber capacitor reduces voltage build-up across switch when turned off.*

The high current through the IGBT during its “On” time creates a flux field around the conductors to it. As illustrated in Figure 3, when the switch device is suddenly opened up, the inertia of the current (inertia = inductance) continues as it builds up the voltage across the stray capacitance from the drain to the
source ($C_{DS}$ in this FET case). Since the capacitance is very small the voltage builds up very quickly and very high. It could easily build up to a magnitude greater than the breakdown voltage of the switch resulting in a defective circuit. The snubber capacitor adds capacitance to the stray capacitance such that the charge built up results in much lower voltages. A resistor is normally placed in series with the snubber capacitors to suppress any ringing. Although the larger the capacitance the lower the voltage created, this capacitor is selected for a value that will keep the generated voltage safely below the breakdown capability of the switch. The pulse voltage across the capacitor will be generated with a high current or with a very large $dv/dt$. The capacitor must be chosen to withstand this peak current or $dv/dt$, and film capacitors are very prevalent in this application.

**DC Link**

This application can easily be called power decoupling. The purpose is to maintain the DC bus voltage during very high current pulses when the IGBT devices switch on. Because this capacitor deals with very high pulse current and the IGBTs operate in lower frequencies ($\leq 25$ kHz), this realm is dominated by film and aluminum electrolytic capacitors. Table 1 highlights the differences between film and aluminum electrolytic capacitors. Putting aside life considerations and self-healing capabilities, the key consideration is voltage. For low voltage DC sources, the aluminum electrolytic is the dominant type because it is considerably less expensive than the films.

| **Table 1:** Comparing film versus aluminum electrolytic for DC Link applications. |
|-----------------|-----------------|-----------------|
| **Parameter**   | **Film**        | **Electrolytic** |
| Life            | Well over 100 k-hours | Up to 100 k-hours |
| Voltage         | Up to $1300$Vdc (C44U series) | Up to $550$Vdc (3 x 450 Vdc in series = 1350 Vdc) |
| ESR             | Low             | High            |
| Ripple Current  | High            | Low             |
| Capacitance     | Low             | High            |
| Energy Density  | $0.16$ J/cm$^2$ (C44U series) | $0.8$ J/cm$^2$ |
| Costs           | Raw material dependent higher | Raw material dependent lower |
The electrolytics can be cascaded to achieve higher voltages, but the net result of this solution increases piece count, handling, and volume. This soon creates a point where the film capacitor becomes cost competitive.

![Cascading Electrolytics Diagram](image)

*Figure 4: Achieving higher voltage capability through cascading for electrolytics.*

Another factor to be considered for aluminum electrolytic capacitors includes the wet electrolyte. The electrolyte can dry out over time, creating a higher ESR and lower capacitance (higher reactance and higher impedance) which may have to be compensated for as in Figure 4. This can lead to higher heating in the capacitor which degrades the life capability. The heat also accelerates damage to the dielectric, and the repair of that dielectric creates gas, which builds up pressure in the capacitor and this can lead to leaking of the electrolyte to the surrounding areas of the capacitor.

Among the film types available for this application include the individual box types for PCB mounting, aluminum can types for modular configurations, and the “brick” designs for specific customers.

<table>
<thead>
<tr>
<th>General Construction</th>
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<tbody>
<tr>
<td>Typicals rated voltages: 600-700 Vdc</td>
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<tr>
<td>900 Vdc</td>
</tr>
<tr>
<td>1100 Vdc</td>
</tr>
<tr>
<td>1300 Vdc</td>
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| Typologies: |
| Mainly dictated by the layout and the mechanical needs: |
| Individual or Box types for PCB mounting |
| Most adaptable, least expensive |
| Aluminum Can types for modular configurations (cable and bus bar) |
| Cheaper than brick if less than 2000 µF required |
| Less efficient in terms of dimensional occupation/flexibility of form factor |
| Brick for the best dimensional efficiency (cap density/volume) |
| Can work at higher power/temperatures due to the special soft winding capacitive elements used that optimize the thermal dissipation |

*Figure 5: Film capacitor type for DC Link Applications*
The brick design incorporates special packaging, including multiple capacitor structures within the potted casing, and terminations designs to optimize inductance for peak current and dv/dt considerations. These are intended to be mounted adjacent to the IGBT assembly to eliminate and connective inductance.

- **“Soft-winding Brick Thin Film**
  - Dielectric: metalized polypropylene (PP) film, thickness <3.5μm
  - Winding: non-inductive type with flattened oval shape
  - Case: plastic or metal material
  - Terminals: high current screw or tinned copper bus-bar

- **“Stacked” – Brick**
  - Dielectric: metalized polypropylene PP and Polyethylene terephthalate PET
  - Winding: non-inductive type with several stacked cut elements
  - Case: plastic or metal material
  - Terminals: high current screw or tinned copper bus-bar

![Figure 6: Specialized “brick” designs for automotive applications.](image)

The aluminum electrolytic types used in this application include the “snap-in” for PCB mounting and lower power, and the screw-terminal for medium to higher power.

### General Construction

**Typologies:**

**Snap-In types for low power drives/inverters/UPS, PCB mounting**
- ALC10, ALC40 (European manufacture)
- PEH508, PEH536 (Chinese manufacture)

**Screw Terminal for medium to high power drives/inverters/UPS**
- ALS30/31, ALS40/41, PEH200, PEH169 (European manufacture)
- ALS32/33, ALS42/43 (Chinese manufacture)

All electrolytic capacitors manufactured using extended cathode construction for enhanced thermal dissipation.

![Figure 7: Typical aluminum electrolytic capacitors for the DC Link application.](image)
**Summation**

The drive function in hybrid and full electric automotive functions include capacitors for filtering, snubbers, and power decoupling (DC Link). The operational frequencies are usually near or below 25 kHz, and in this frequency realm with requirements of high capacitance, the preferred choice among capacitors types is narrowed to aluminum electrolytic and film capacitors. The aluminum electrolytic is less expensive than the film, but carries limitations in performance, voltage capability, and reliability. The final solution will depend on the specific application and circuit design, along with cost, performance, and reliability expectations.

**Bibliography**