New Power Capacitors for HEV Converter Applications

The HEV motor output rose from 20 to 30kW in the year 2001 up to 140kW in 2006, the rated voltage started at 100 to 300VDC and has reached now 750VDC, and the capacitance values now range from 500 up to 3000µF. Modern HEV converter design strategies are trying to find alternative options for the once popular Electrolytic capacitors. The newly developed product family of capacitors, called PCC, uses a unique flat and wrinkle-free stacked technology in PEC format and extending the small stacked capacitor sizes that have been well known for decades. This technology helps to optimise the converter designs to reach self-inductance values well below 20nH due to integration of the busbar into the capacitor construction, avoiding oscillatory operation at the switching frequency. **Harald Vetter, EPCOS, Heidenheim, Germany**

The development for Hybrid- and Fuel Cell Powered Drives shows a ramping up tendency of V_r and has now reached the common level of $V_r \approx$ 750VDC based on a C_r - range of 0,4 up to 3mF. The design strategies of modern HEV converters can now be built around the new alternative option of PCCs (Power Capacitor Chips), leaving out the once popular Electrolytic Caps which had the advantage of high values for U_r below 450VDC (Figure 1). A well known example for the change to Film Capacitor technology is Toyota's power converter: PRIUS-I was equipped with Electrolytic Capacitors; PRIUS-II includes a film capacitor module with expected data of 600VDC rated voltage, rated capacitance of 1130+282+0.1µF, 3µm Polypropylene film, dry and resin filled, weight approx. 3kg.

System designers always have the challenge to realise increased output power within a smaller system volume. The target at the beginning of 2010s is less than 1/2 of volume to the current technology (see Figures 2 and 3). This target allows flexible installation of the power converter, so that 'HEV-versions' of the existing conventional vehicles can be provided.

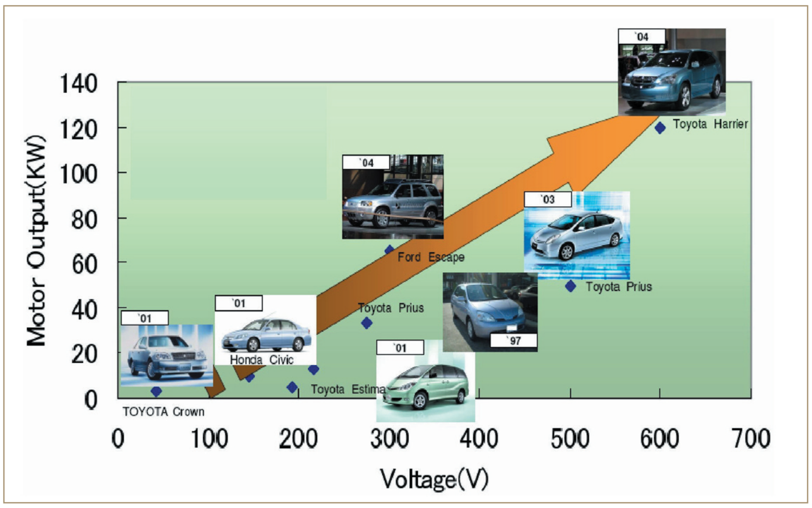

Figure 1: The tendency of rated voltage in an HEV is growing; the LEXUS-2006 design, for example, has now reached 750VDC

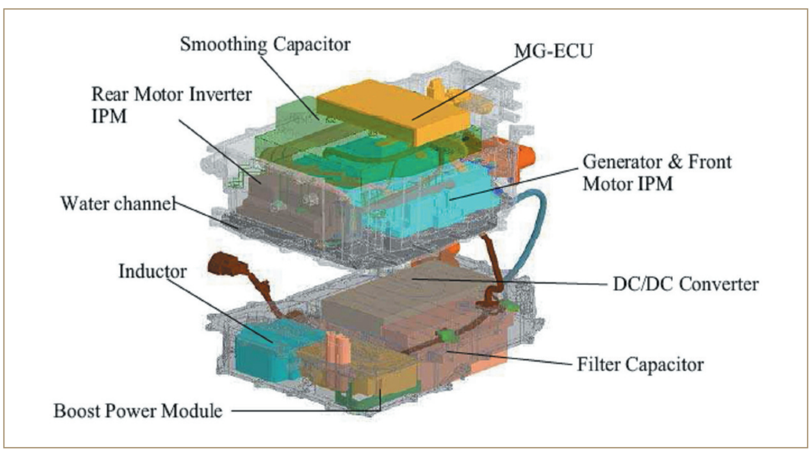

Figure 2: The power converter design of LEXUS-2006 is going towards mechatronic integration. The DC-link capacitor and the motor controlling ECU are located on the upper part of the converter. The generator, the front- and rear motor IPM is mounted on the upper surface of the water cooling channel. The boost power module, inductor, filter capacitor and DC/DC converter are located on the lower surface of the converter

Load and capacitor size

For optimum dimensioning of the power capacitor in the HEV converter, a mission profile is an important requirement and should be based mainly on the drive cycle loading data. NEDC (new European drive cycle) is such a typical drive cycle; in addition there are different drive cycles associated with the various operating tasks of the vehicle. NEDC represents a typical driving situation; the running time of 1200s or 0,33h is important. The mission profile

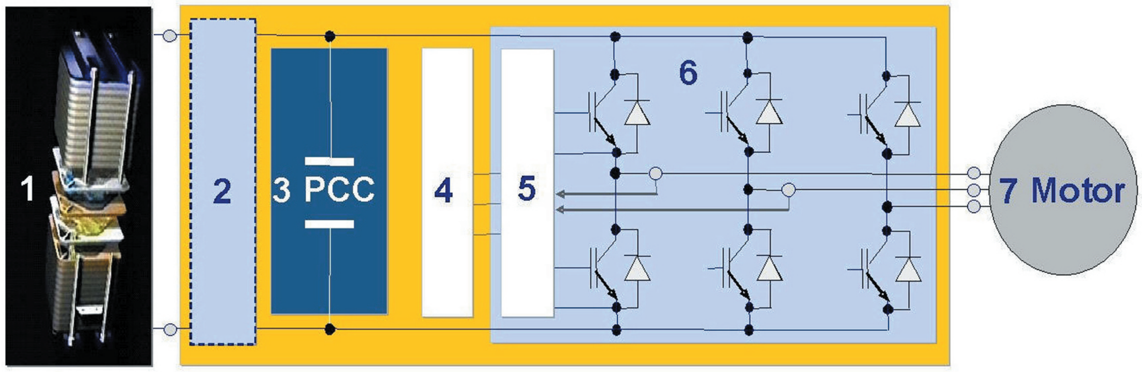

Figure 3: **Topology of an automotive power train converter with energy source and a PCC DC-link capacitor with 1) Fuel Cell or HV-Battery, 2) EMC filter (with some PCC designs not necessary), 3) DC-link PCC with integrated bus bar, 4) Drive control bus interface, 5) Monitoring & protection gate driver, 6) IGBT bridge with integrated cooling & sensors**

should be adapted to the overall vehicle cycle and form a model of the daily system load. The known load profiles for HEV converters require - depending on vehicle type - a load time t_L between 6000 and 12.000 hours and about 15 years standby (or 300,000km). Of particular importance for the capacitor design is the fact that the drive cycles generally are significantly shorter than one hour and are, thus, smaller than the thermal time constant T_{th} of the PCC capacitors under consideration here [1].

HEV converters have to bear the main loads in the time periods involving speed changes. During acceleration the DC voltage falls, and during braking it rises again, while the operating current values remain approximately constant, i.e. during a drive cycle there is a discontinuous current and voltage distribution or a pronounced intermittency, see Figure 4. The environmental temperature profile poses a further challenge to the capacitor design; in particular the temperatures above 105°C must be given careful consideration. The ambient temperature T_a is frequently affected by the flow temperature of the cooling medium for the heatsink and must be taken into account, see Figure 5.

Thermal design of PCC

The thermal loads on the capacitor can be classified into slow temperature changes and temperature shock. The distribution of the ambient temperature, the load current and the voltage together with the mission profile is important for the lifetime calculation and for determining the required dielectric thickness.

The power dissipation P of the capacitor is calculated with equation 1, the dissipation must be calculated for each fraction of time together with the mission profile.

$$P = \hat{u}_w^2 \cdot \pi \cdot f_o \cdot C_r \cdot \tan\delta + I^2 \cdot R_s + U_r \cdot i_{isol} \qquad (1)$$

where U_r is the rated voltage, û is the half peak to peak-, f_0 is the fundamental frequency, I is the rms current of the capacitor C_r, i_{isol} is the isolation current R_s is the series resistance which is producing with the rms current the ohmic losses.

The thermal resistance R_{th} e.g. is depending of the cooling situation, the geometrical aspects (dimensions) and the capacitor design (casing material and impregnation e.g. resin filled or naked - oil in automotive delivers too high P_{isol} values). However, after calculation and evaluation due to a heat run we will get the results for equation 2 to be able to predict hot spot temperature T_{hs} via equation 3:

$$R_{th} = \Delta T_{hs-a} / P \qquad (2)$$

The parameter a, R_s and R_{th} for two standard automotive PCC are filed in Table 1.

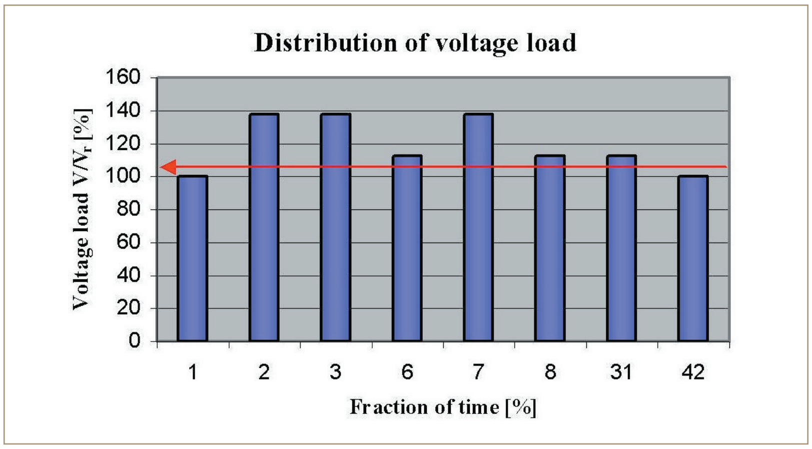

Figure 4: **NEDC based distribution of the capacitor voltage and the lifetime relevant voltage level for the capacitor (red)**

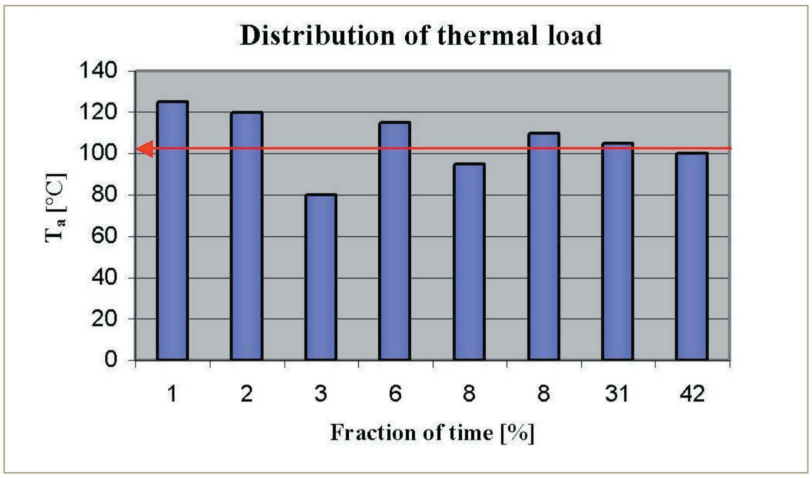

Figure 5: **NEDC based distribution of the capacitor ambient temperature with the lifetime relevant temperature level (red)**

C_r [mF]	a [µm]	R_s [mΩ]	R_{th} [K/Watt]
0,4	3	1,6	5
3,0	3	0,5	1,8

Table 1: Parameters a, R_s and R_{th} for two standard automotive PCCs

$$T_{hs} = T_{amb} + R_{th} \cdot P \qquad (3)$$

For the intermittent operation, the transient thermal resistance Z_{th} (equation 4) delivers the max hot spot temperature $T_{hs\,max}$ after a power pulse. With a thermal time constant of $t_{th} \approx 1h$ and a loading time of <= 1h e.g. about 63% of full load T_{hs} will be reached.

$$Z_{th} = R_{th}(1 - e^{\frac{-t}{\tau_{th}}}) \qquad (4)$$

For the design in process we respect the limit where T_0 is the max possible T_{hs} for the discussed design. Afterwards a lifetime calculation is necessary.

$$T_{amb} \leq T_o - (R_{th} \cdot P) \qquad (5)$$

For IGBT converters in general and especially HEV powered drives an extremely low loop inductance in the level of L_σ = 5 up to 20nH is important.

A new winding technology

The newly developed winding technology can be used to implement absolutely flat and wrinkle-free stacked windings in 'power cap dimensions' for PCC using metallised polymer films, starting with PP down to 2µm and PET 1,5µm (Polyethyleneterephthalate is mainly for T_{max} <= 135°C designs and will be 'preferred' at low to medium V_r values), see Figure 6 and 7). The PCC process line with a polygon winder is able to wind at least four metallised films, an important point for a high efficient production. A 'wavy-smooth' cut combination maximises the effective contact area via a defined small offset and precisely wound master capacitors. The result is an outstanding pulse-current-handling capability without the contact edge problem, which is a well-known failure potential at the film edges of low-cost MKP windings.

The rated voltage and capacitance ranges from 100 to 1000VDC and 100 to 3000µF depending on the system requirements. Standard- and custom-design solutions such as an integrated busbar will give the system designers additional scope to optimise their inverter layout in order to achieve high peak- and rms current handling capability; high over-voltage strength up to 2 times V_r; extremely low inductance; high permissible ambient temperature; miniaturising due volume fill factor ≈ 1 ($V_{FF} = V_{physical}/V_{technical}$); easy to integrate into a converter casing; low functional weight; low fire hazard due to liquid free technology; long expected service life; and no acid inside and no storage problem. Figure 8 shows a new 2nd generation HEV converter using a circular shaped 500µF PCC (U_R = 450VDC, I_{th} = 200Arms, d = 270mm and an integrated busbar) with a Y-capacitor function. Here, the stray inductance between the power semiconductors and the PCCs has to be minimised, hence the DC-link capacitor is distributed between the IPMs around the circular converter assembly. To make full use of the available space the PCC were built in a circular form by winding the foils with a diameter corresponding to the diameter of the circular converter, realised together with ECPE.

Conclusion

Power Capacitor Chip is based on the well known MKK-Technology which is a dry, self healing capacitor, but with a new stacked winding technology in power cap format. PCCs will be produced as a complete subsystem e.g. with an integrated bus bar as well. Power electronic circuits with PCC don't need additional decoupling caps to gain lowest

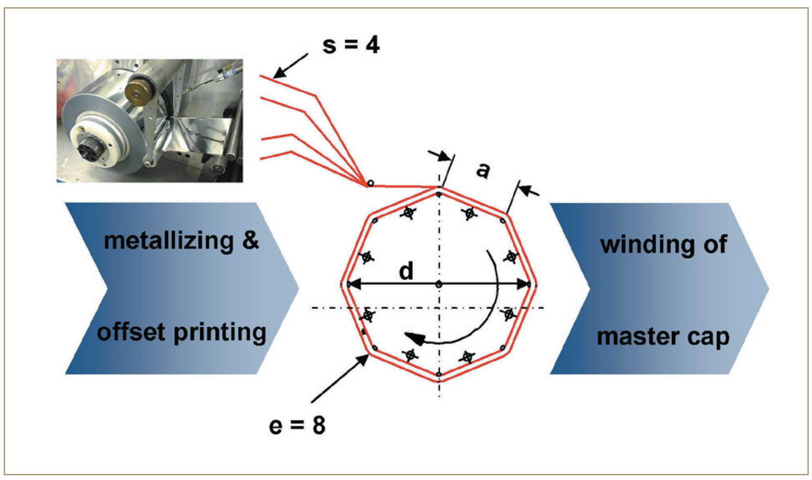

Figure 6: Process flow of PCC winding

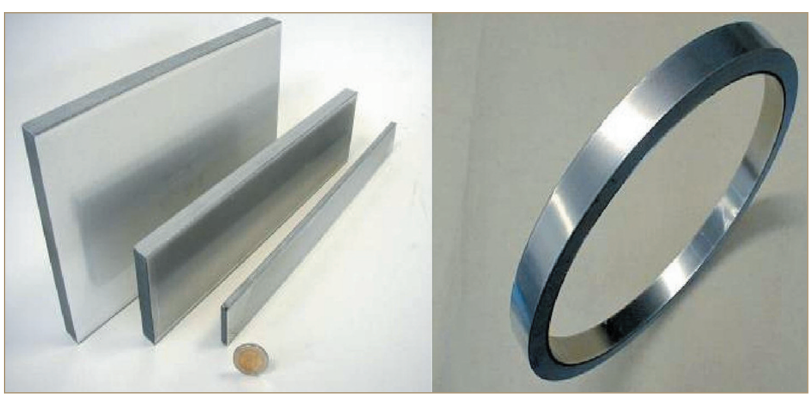

Figure 7: PCC features extremely dimensional flexibility from a flat stack winding in power cap dimension up to circular shaped large diameter

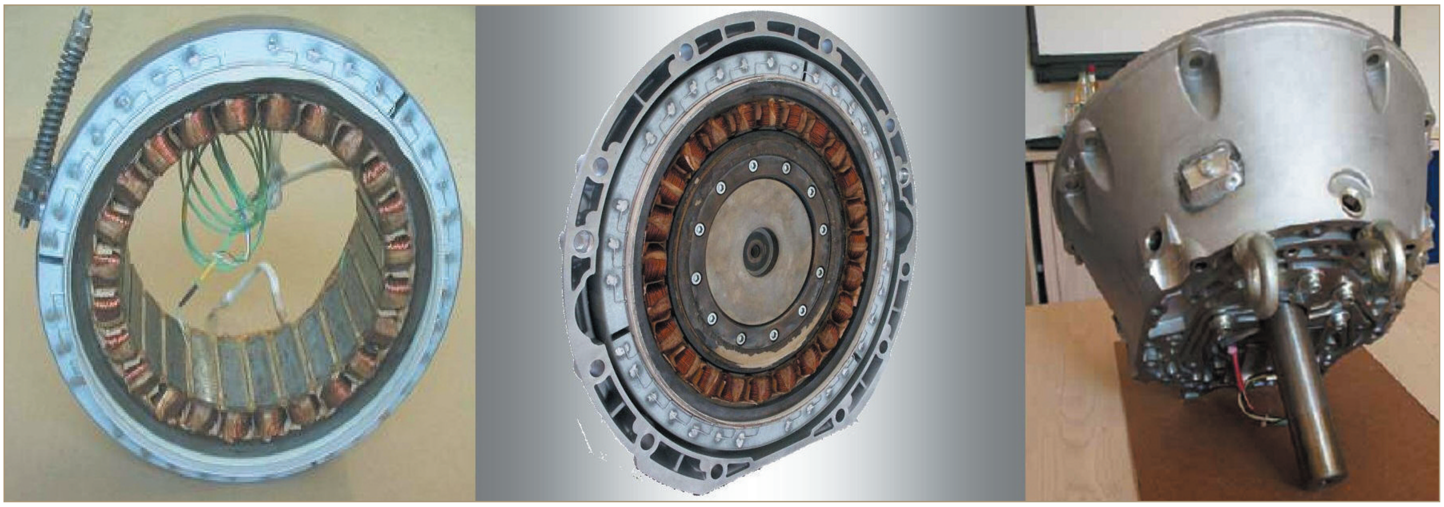

Figure 8: A new HEV converter 2nd generation using a circular shaped PCC with $C_R \approx$ 500µF, U_R = 450VDC, I_{th} = 200Arms, d = 270mm and an integrated busbar with a Y-capacitor function

loop inductance values. This technology can also be used to replace electrolytic capacitors and it is evident that this ultra compact capacitor - often made in a single block shape - is a best-case design for a miniaturised automotive power electronic solutions. The dimensional flexibility allows customised designs and satisfies hitherto unfeasible size requirements and PCCs delivers outstanding performance data like very low ESR and ESL values. The development trend characterised by the extreme requirements of fully integrated HEV converters will be supported by improvements in plain film performance data, the use of with new coating processed films, the upcoming down gauging of film thickness on the PP-polymer, and the reduction of power losses due to optimised profile metallisation techniques like structured cross section profiled metallisation. This requires a high-quality, cost-effective production process with ultra thin film handling handling capability for boosting PCCs in industrial and automotive applications.

Literature

[1] Mission Profile based PCC Design for Integration into HEV-Converter, Harald Vetter, EPCOS AG