

# Options for Electric Power Steering Modules a Reliability Challenge

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**Abstract:** Electric and Electro-Hydraulic Power Steering Systems (EPS / EHPS) are gaining more and more momentum. They have substantial advantages over conventional hydraulic steering systems. In particular, EPS can improve comfort, safety and energy-efficiency of any car. The market share of these systems increases every year.

The typical core component of an EPS system is a three phase brushless electric motor with power rating of up to one kilowatt. The drive system is highly dynamic and can draw more than 100 Amperes from a 12 Volt automotive power grid.

EPS systems often are subjected to a 120°C ambient under-the-hood environment. Specific mission profiles (e.g. "driving school circuit") and are a special strain for the thermal design of an EPS control unit. These factors describe a very demanding current and temperature profile for the PWM inverter power stage.

Traditional discrete assemblies often exceed physical limitations and do not offer the reliability needed. In thermally dynamic applications, such as EPS, discrete semiconductors often suffer from limited silicon die size, direct Cu-bonding, CTE-mismatch and insufficient cooling. The bottleneck of discreties is not the silicon allowing junction temperatures of 175°C, but the bonding and joining technologies to connect and cool the MOSFET dies.

Special semiconductor power modules, e.g. comprising of six transistors, current- and temperature-sense, can overcome these limitations. They provide the reliability needed to survive the whole automotive lifecycle of up to 20 years. A range of special module packages is suitable for EPS applications and will be described in this article. Three proven architectures are part of the solution matrix:

- ❑ Bare-die assemblies on ceramic substrates
- ❑ Cu-baseplate modules with bondable frame
- ❑ Transfer-molded modules

The article analyzes the advantages and disadvantages of these designs. Different parameters, e.g. cost, thermal cycle-capability, robustness for assembly and integration into an ECU are discussed.

**Keywords:** Electric power steering, EPS, EHPS, MOSFET, power module, reliability, cooling, bonding and joining technologies

## 1. Applications and market requirements

One decade ago the first electric power steering systems were introduced into the market. The initial designs were still hydraulically amplified steering systems, but a DC motor drove the hydraulic pump instead of a pulley taking power from the fan belt. In addition, a couple of compact cars arrived to the showrooms, comprising a brushed DC-motor directly assisting the steering rod.

The Electronic Control Unit (ECU) including the power stage was in first instance a separate device, connected to the motor by a wiring harness. More recent designs integrate the ECU into a monolithic unit of control, powerstage, motor and gearset, that can be directly installed to the steering rack, pinion or column

The following fundamental market trends can be derived:

- ❑ PM-Motors / AC drives substitute DC drives
- ❑ Integrated ECUs substitute separate ECUs
- ❑ EPS / EHPS grows from compact cars to heavier class C / D / E and SUV segments and power ratings are increasing
- ❑ More severe operating conditions (temperature) for power stage, while focus on safety and reliability remains on highest level
- ❑ For a new generation of cars with hybrid-electric drivetrain or start-stop system an electric power steering is compulsive

- ❑ Additional comfort / safety features like superimposed steering and rear wheel steering will require high-power electric actuation

A fundamental scope is on finding the right trade-off between cost, performance and the imperative reliability.

Globally, about 10 major steering system suppliers of are working on electric power steering. They rely on a couple of experienced partners specializing in customized electronic components.

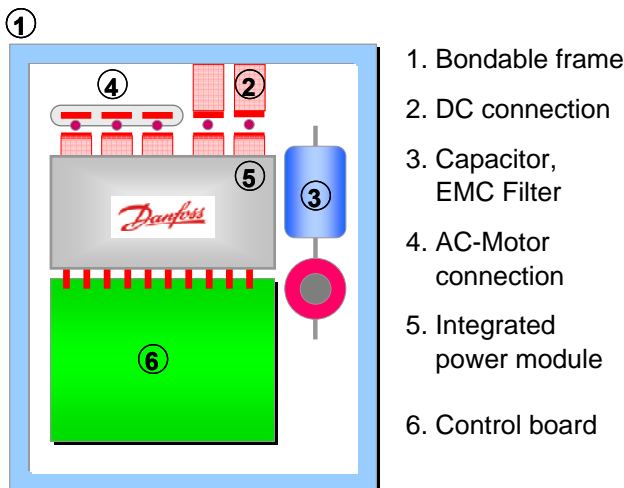
## 2. Power Electronic Requirements

The design of an electronic control (ECU) unit for power steering systems starts with a careful description of the mission profile and environment of operation.

The fundamental difference between a direct drive EPS and a pump-operated EHPS is, that true servo application EPS puts a higher current- and temperature-cycling profile on the power stage of its control unit.

In contrast, an electro-hydraulic unit usually operates on continuously low revs to sustain a specific system pressure. In case of high demand for steering aid, the pump powers up to provide maximum output.

Typically, the maximum load is described by an outstanding test scenario, e.g. a parking lot test with repetitive high steering demand under concurrent high ambient temperature load.



**Figure 1: Example of an ECU (Electronic Control Unit) for Electric Power Steering**

The designer of an ECU must blend these external requirements with space and cost constraints in the control unit. To survive the described harsh test and operating conditions, a proper thermal management of the device is highly relevant.

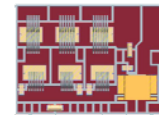
In the past often one single type of circuit carrier, e.g. glass-epoxy (FR4) or thickfilm-ceramics were sufficient to arrange the whole componentry of an ECU. Since currents are increasing substantially, specialized substrates for signal and power stage are moving into modern ECUs.

Dedicated power modules allow to increase power density and can dissipate up to 10 W / cm<sup>2</sup>. Alongside, they can be designed to take the strong thermal cycling loads coming for the extensive servo operation.

## 3. Solution Overview Power Modules

### 3.1 Bare DBC Substrates

The most simplistic PWM-power-stage can be demonstrated by a populated DBC-substrate. These substrates typically comprise a MOSFET six-pack to drive a three phase motor. MOSFETs are typically soldered with a virtually void-free alloy, that gives sufficient headroom between maximum operating temperature and the solder melting temperature.

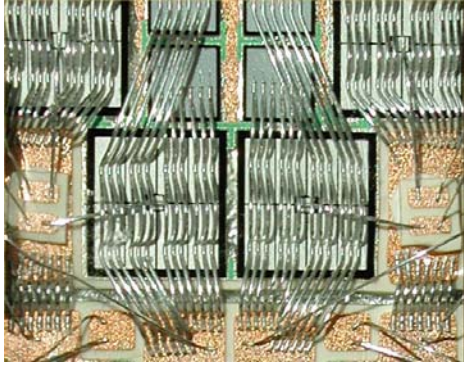


**Figure 2: Bare DBC-Substrate with MOSFET-Transistors for glue-on-assembly**

The proven Al<sub>2</sub>O<sub>3</sub>-Substrates with a thermal expansion coefficient of 7-8 ppm/k are matching well with a silicon die of about 3 ppm/k.

Ceramic substrates provide excellent isolation up to several thousand volts and are good heat conductors. The thick and homogenous Cu-coating on the DBC's front and backside provides a good temperature distribution, lateral spreading and very low ohmic losses.

Compared to usual 100 μm thickfilm-copper-glass-paste hybrids the electrical conductivity of a DBC is about 6 times higher.



**Figure 3: Multiple large wire bonds provide current distribution and minimised losses**

In addition, MOSFET semiconductors can be generously covered with a maximum of large-wire bonds in order to minimize ohmic losses and unwanted heat dissipation by eliminating hotspots.

Unlike the simplistic nature of this device, its assembly is slightly more complicated than other alternatives.

The pre-soldered DBC-substrates have to be glued on a heat sink under very controlled conditions. Thermal conductivity of the glue layer and its physical coherence are vital to the overall thermal performance. After the glue is temperature-cured, the DBC can be connected to the external control- and power-contacts with large-wire bonding. Finally, the device has to be protected with a silicon-gel cover on open dies and bond-feet. These processes require an above-average precision and cleanliness compared to standard electronic assemblies.

### 3.2 Cu-baseplate modules with bondable frame

A more sophisticated and extended version of the bare DBC is a power module with added copper baseplate and a bondable frame for external electrical connection of the power-stage.

Here, the DBC is thermally linked to a Cu-plate by a large-area solder layer. The copper now helps to buffer and to spread heat dissipated by the MOSFET dies.

An external frame allows connecting the module to the external circuit by welding or soldering. The com-

plete housing of semiconductors gives the module additional robustness.

Thermal buffer properties of the Cu-baseplate allow for less rigid requirements with regard to an even heat sink surface or to the tolerance of the applied thermal interface material (TIM). Overall, the added module complexity allows for simplified assembly and cost savings in the periphery.



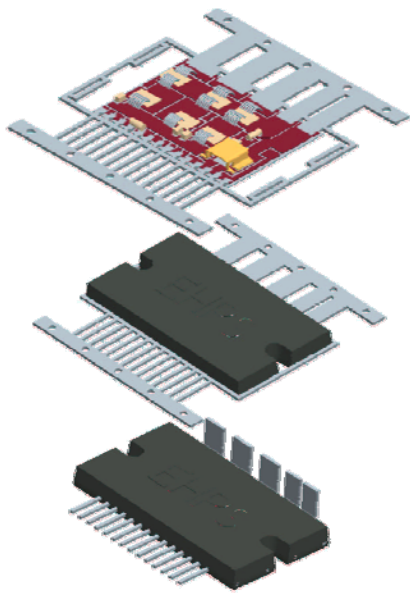
**Figure 4: EPS Power module with Cu-baseplate and bondable frame**

### 3.3 Power-Module with transfer-molded housing

Discrete and integrated components with a mold resin encapsulation have a long tradition in electronics.

With advanced duroplastic materials the industry can today produce power modules comprising a complete sixpack inverter stage with MOSFETs or IGBT. Key to these large-scale components is a mold compound with adapted thermal expansion coefficient CTE as well as low shrinkage.

The finished mold package is very rigid and allows to easily assembling the modules with standard electronic manufacturing lines.



**Figure 5: Molded module in die-on-substrate technology in different production steps**

Two fundamental variants of power modules are available:

- A Module comprising a molded DBC in analogy to 3.1. together with an integrated leadframe allowing for external contacts. Here, the DBC is both a perfect isolation for voltage and a thermal interface to the heatsink
- A Module comprising of a leadframe only. This layout separates different segments of the leadframe for different circuit potentials. Semiconductors are directly soldered upon the copper surfaces. This leadframe can only be assembled on a heatsink with an electrically isolating layer of glue or thermal interface material. It is basically limited to low-voltage Mosfet applications.

#### 4. Reliability Discussion

Designing a power module for “under the hood” applications is a challenge for several reasons:

First of all the physical environment for the power module is extremely harsh featuring high ambient temperatures (in excess of 100°C, up to 5-600°C near the exhaust), vibration, humidity, salt mist etc. Secondly because the designer works under a tremendous cost pressure (the way of life in automo-

tives) meaning that it is a challenge to afford a sufficient amount of power silicon that would enable a reasonable low thermal resistance. Thirdly because size matters: The designer is most often required to integrate the power module in an ECU within a very limited space available; this by the way often rules out other technical solutions like discrettes on IMS.

Thus the design process is based on a number of tradeoffs and compromises, e.g. longer life demands bigger silicon chips but that drives cost and size the wrong way.

The degradation of power electronic devices under high current densities (consequently high power dissipation) can be traced to several different load categories:

- ❑ Continuous operation with small variations in the current profile
- ❑ Single short time events with max current demand (period: few seconds)
- ❑ Groups of load variations over several seconds to minutes

In automotive application all 3 types of load pattern can be observed. Most of the power electronic applications are defined by specific load profiles.

- ❑ Hydraulic power steering: continuous operation plus groups of load variations
- ❑ Electric power steering groups of load variations of short duration
- ❑ Start/Stop systems: Single short time events within 1 second
- ❑ Mild hybrids: Single short time events plus groups of load cycles
- ❑ Strong hybrids: Mostly continuous operation plus groups of load cycles interrupted by single events

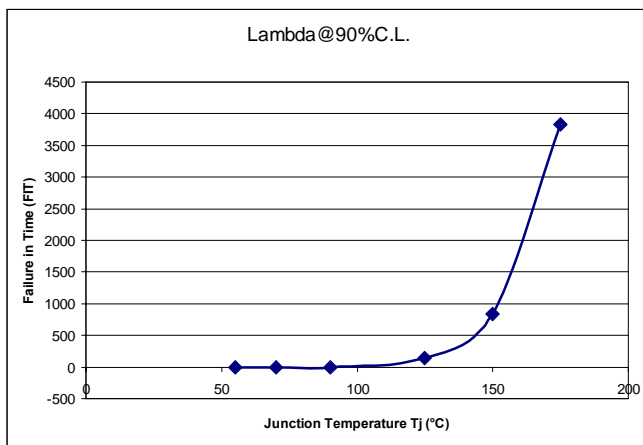
Typical failure modes of power modules are to be found in the assembly of the semiconductors and materials of the thermal stack. It is possible to dedicate specific failure modes to specific load cycles:

- ❑ Bond wire lift-off is caused by current switching between  $>0$  s and  $\sim 3$  s
- ❑ Die-solder layer is cracked by current load cycles between  $\sim 5$  s and  $\sim 20$  s
- ❑ Large area solder layer degradation of the substrate is observed for temperature changes between 600 s to 6,000 s

The lifetime of a power module is predetermined by the number of temperature cycles (of a definite temperature swing) a specific thermal stack is capable to survive. All failure modes are heavily accelerated by the level of operating (ambient) temperature: The higher the ambient temperature, the higher average operating temperature and the more destructive the failure modes are addressed by the different load cycles.

#### 4.1 Device temperatures

The importance of device temperature is demonstrated in the study by ST microelectronics.



Source: ST-Microelectronics Reliability Report 2002

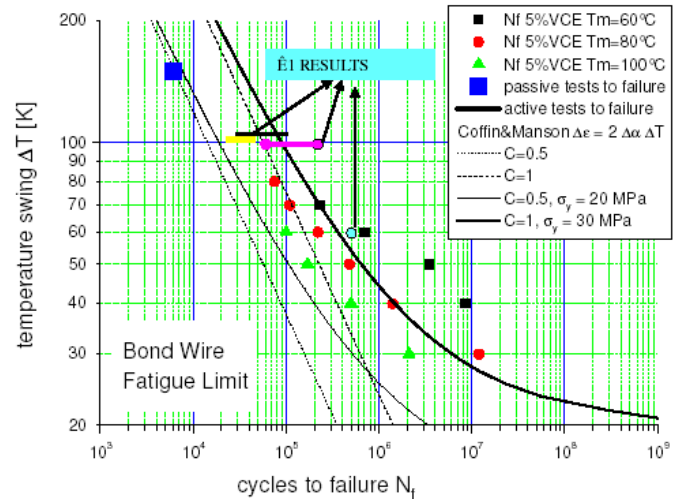
**Figure 6: FIT vs. junction temperature**

Here it is seen that the failures in time start to increase dramatically at junction temperatures above 120-130°C. The trend in the semiconductor business towards higher and higher device temperatures, approaching and even surpassing 200°C should be taken with great precaution. The bonding and joining technologies need to follow troop and this generates new challenges.

#### 4.2 Wire bond failure

One of the lifetime limiting factors is the wire bond connection; it turns out that fast temperature cycles (power cycling) create so called bond wire lift offs. This is caused by the mismatch in the coefficient of thermal expansion (CTE) between the silicon chip (CTE = 3 ppm/K) and the aluminum bond wire (CTE = 24 ppm/K). As the temperature changes this mismatch will create stresses and strains in the Si/Al interface which again lead to fatigue cracking. The larger the temperature swing the fewer cycles to failure. This phenomenon is well understood and

most often modeled using a Coffin & Manson approach [3]. The chart below shows the relationship between the number of cycles to failure and the size of the temperature swings.

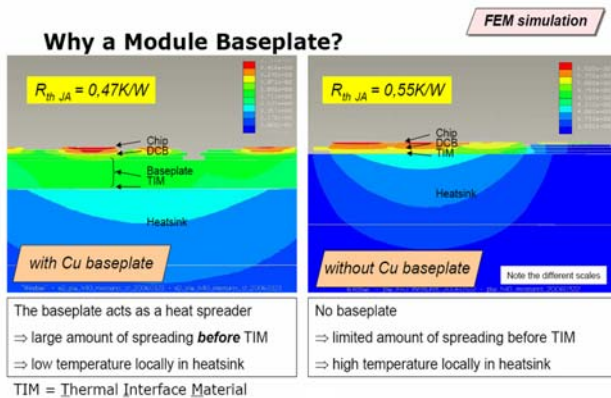


**Figure 7: The relationship between the number of cycles to failure for a wire bond and the ΔT.**

Also seen in the Coffin & Manson chart is the dependency of the mean temperature around which the temperature swings occur: the larger the  $T_m$  the shorter the life even for the same  $\Delta T$ ; the chart features three sets of test results performed at different mean temperatures (60°C, 80°C and 100°C). This shows that good control of the mean device temperature is important in the second order: good cooling reduces the  $\Delta T$  but also the level,  $T_m$ , where it occurs.

#### 4.3 Baseplates and large area solder joints

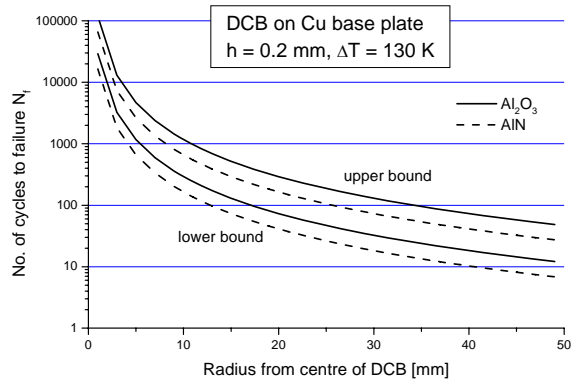
Therefore the semiconductors have to be cooled as effectively as possible, meaning that the thermal stack, which defines the materials and geometries from junction to ambient, must be optimized. As an example designing the power module with a copper baseplate offers a better thermal performance as shown in the figure below:



**Figure 8: Effect of having a copper baseplate.**

The baseplate helps spreading the heat over a large area before the heat passes through the inevitable thermal interface material (TIM) thus improving things considerably: the thermal resistance and thus the junction temperature will become lower and life will be longer because the wire bonds will experience smaller  $\Delta T$ 's at lower  $T_m$ 's. Power modules having a baseplate are less sensitive towards the quality of the TIM, like thermal conductivity, thickness variations and voids, compared to "DCB-only" modules. Additionally the baseplate offers a quality of ruggedness to the power module: the delicate DCB substrate will much less prone to breakage when riding a baseplate.

Introducing the baseplate in the power module does not solve all problems though, it even creates new problems. The most important is that the large area solder joint between the DCB substrate and the baseplate too is damaged by temperature cycles. But whereas the wire bonds suffer from a large number of fast power cycles, it is the slow temperature cycles, arising from daily climatic changes combined with cold starts of the car, that threaten the integrity of the large area solder joint. The failure mode is well understood and it too can be modeled using Coffin&Manson approaches [4]. An example is shown in the chart below that shows the relationship between number of cycles to failure and the size of the solder joint.



**Figure 9: The relationship between the size of the DCB substrate and the number of cycles to failure for a large area solder joint.**

It turns out that  $N_f$  is inversely proportional to the size (radius) of the solder joint squared and proportional to the thickness squared. This means that  $N_f$  is quadrupled by doubling the solder thickness but reduced to 1/4th by doubling the size (radius) of the solder joint.

Designing for optimum solder joint reliability involves optimizing the size of the solder joint i.e. length, width and thickness.

#### 4.4 The mission profile of power steering applications - Requirements

Understanding all the relevant failure mechanisms of the power module assembly and knowing the load conditions that the module will see during its life of operation, *the mission profile*, are the keystones for the most optimum design of the power module.

The design process is an iterative one: The temperature cycles that define the mission profile are analyzed individually regarding their damaging effect on the wire bonds, solder joints etc.; the sum of these individual damaging effects then form the overall damaging effect arising from the mission profile.

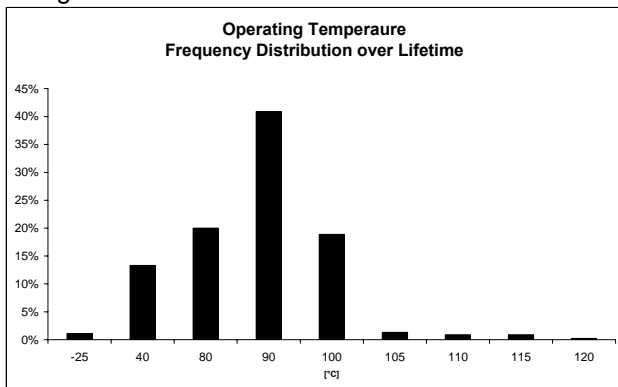
If it turns out that the power module will fail too soon, e.g. by wire bond lift off, the thermal design must be improved as to lower the size of the temperature swings and/or by lowering the mean temperature. This most often demands larger silicon chips and/or an improved cooling.

If, on the other hand, the power module will survive the loads defined by the mission profile by too large a margin, the module is thermally oversized and thus

too costly. The thermal stack must be trimmed down e.g. by reducing silicon area.

The basis for the thermal design approach described above is the specification; a clear definition of the mission profile is crucial in order to do an optimum design that will withstand the required load cycles without being “overkill” and a too costly design.

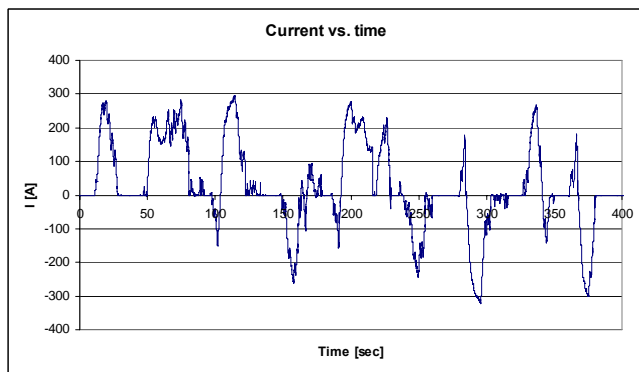
One of most important information for the module designer is the number of operating hours and the temperature level. Typically the demand is 6,000h of operation under varying boundary conditions of ambient temperature and load induced temperature swings.



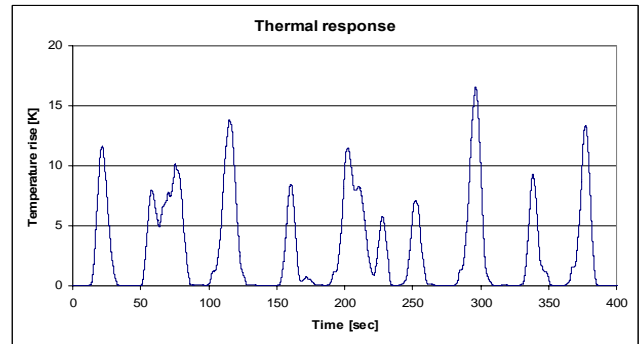
**Figure 10: Operating temperature as frequency distribution of lifetime**

A typical assumption for the ambient temperature is 34% of the operating period is below 85°C, 63% of the time the ambient temperature is between 80°C and 100°C and only 3% above 100°C

The second step is to define a real or at least realistic load cycle followed by transformations from current profiles into power losses profiles and from there to temperature swings at a given ambient temperature.



**Figure 11: A logged current profile of an electrical vehicle in movement. Note the negative current during recuperation**

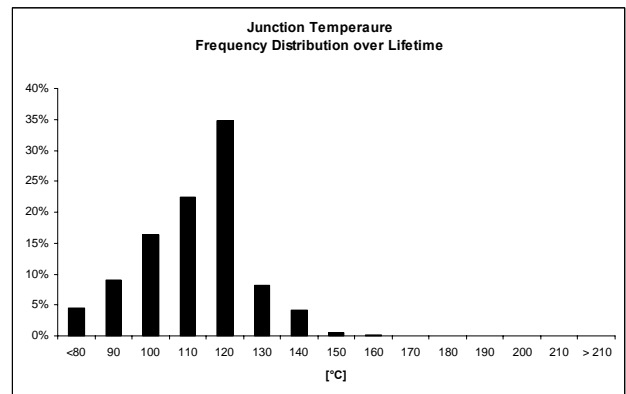


**Fig. 12: Thermal response of the junction temperature of a MOSFET of an electric vehicle deducted from the current profile and the Rth of the power module in the system**

The temperature change by power losses of the device (see Fig. 12) and ambient temperatures of 80°C to 110°C leads junction temperatures up to 160°C (see Fig. 10) is the critical factor for the degradation.

The following graph indicates the estimation of the frequency distribution of the junction temperature in a power steering module during 6000 hours of operation.

Junction temperature does not exceed 160°C under worst conditions (lock stop, short circuit, etc. at maximum operating temperature under the hood). This is called a ‘safe design’.



**Figure 13: Junction temperature of a MOSFET power module in a power steering application. Tj is obtained with operating temperatures based on Figure 10**

## 5. Cost drivers


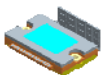

The three different module types have not only different physical characteristics. They differ in cost as well. To find a proper solution, a total cost of ownership-calculation can be recommended.

The bare DBC is obviously least in cost. But its assembly process requires higher investment and / or labor content than the more complex housed variants.

## 6. Conclusion

Danfoss Silicon Power is convinced that a reliable and economic solution will be created holistically, integrating the mechanical, electrical and thermal design of the power module and its application.

EPS Power-Modules compared

	Bare DBC	Cu baseplate	Molded Module
<b>Subject</b>			
1 Thermal Cycles	high <span style="color: green;">●</span>	medium <span style="color: orange;">●</span>	medium - high <span style="color: green;">●</span>
2 Power density	medium <span style="color: orange;">●</span>	high <span style="color: green;">●</span>	high <span style="color: green;">●</span>
3 Thermal robustness	sensitive <span style="color: orange;">●</span>	high <span style="color: green;">●</span>	high <span style="color: green;">●</span>
4 Assembly process	sophisticated <span style="color: orange;">●</span>	standard <span style="color: green;">●</span>	standard <span style="color: green;">●</span>
5 Cost	low <span style="color: green;">●</span>	medium <span style="color: orange;">●</span>	low - medium <span style="color: green;">●</span>
<b>Recommended for Application</b>	EPS / EHPS various drives	EHPS, power management	EPS / EHPS various drives

Source: Danfoss Research

Figure 14: Evaluation overview

In this article, a range of three options was discussed. Each of these has specific advantages. The bare DBC is a very simplistic approach that has been proven in millions of vehicles. Its limitations stem from the thermal stack and a glue-layer that can constrain the cooling of semiconductors.

The copper baseplate module can be considered the "silver bullet" with regard to thermal robustness. No other solution in particular can equal the thermal robustness and tolerance to variations of the thermal interface together with excellent voltage isolation.

A fully molded power module with copper interface is mechanically very robust. Its voltage isolation is restricted to the usual 12-Volt range. In contrast, the thermal buffer capability of a copper leadframe can be superior to the glued DBC variant.

Now it is the designer's choice to make up their individual evaluation matrix!

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