Structures of the Energy flow system

Mekatronics - energiflow

**Structures of the energy conversion system (< 1 h)**
- Primary energy to output
- Electrical as intermediate

**Power electronic converters as components (< 3 h)**
- AC/DC/AC
- Modulation
- Power Units (50 Hz / SMPS / Integration)
- Passive components / Integration of passives

**Electromechanical converters as components (< 3 h)**
- Conv. machine types
- Electrostrictive/magnetostrictive converters
- Cooling
- Power and Energy density

**Energyconverters as construction elements (< 1 h)**
- Laminated steel / powder pressing / injection moulding

**Powerelectronic measurements (< 2 h)**
- Current / voltage / flux
- Torque /speed / position
- Pressure / flow (in pumps)
Energy processed in several steps

- **Primary energy source**
  - (chemical, mechanical, electrical)
- **Intermediate electrical energy storage**
  - (capacitive, inductive, ...)
- **Output energy**
  - (mechanical, heat, light, sound,...)

### Primary energy sources

- **Chemical**
  - Batteries
- **Electrical**
  - Power grid, YY SEK/kWh
- **Mechanical**
  - Flywheel, static
- **Solar power**
  - Max 10…15% @ 1000 W/m²
Primary to intermediate energy conversion

- **AC to rectified DC**
  - 230 V / 50 Hz to almost 325 V (single phase rectifier)
  - 400 V / 50 Hz to almost 540 V (three phase rectifier)
- **AC to low voltage DC**
  - Transformer + rectifier
  - SMPS
- **DC to DC**
  - Non-isolated, step down
  - Non isolated, step up
  - Isolated

AC to rectified DC – 1 phase

- High harmonic content in the line current
AC to rectified DC – 3 phase

- High harmonic content in the line current

AC to low voltage DC

- Step down transformer + rectifier. Still the same problem with high harmonics in the line current.
SMPS – Switched Mode Power Supplies

• **Function**
  - Transistor "on" -> increasing inductor current through transistor
  - Transistor off -> decreasing inductor current through diode

• **Advantages:**
  - Output voltage greater than input voltage (universal input);
  - Simple control;
  - Input inductance acts like a filter toward AC line;
  - Many control ICs available on the market.
  - PFC of 0.95 or better over line and load variations.

Switched mode power supplies for low voltage DC with flyback

• **Features:**
  - Galvanic isolation to the feeding grid
  - Output voltage range adjusted with the transformer ratio

**1-quadrant step down converter**
(buck-converter)

- Output voltage lower than input voltage
- Output current positive
Control of 1-q. buck converter.

1-quadrant step up converter (boost-converter)

- Output voltage (Ud) higher than input voltage
Control of 1-q. Boost converter

http://www.ipes.ethz.ch/ipes/download.html
2-quadrant DC converter

- Both directions for energy flow
  - Voltage unipolar, current bipolar
- Equivalent switch:

\[
\begin{align*}
+ & \quad \text{u} \\
- & \quad \text{i} \\
& \quad \text{L, R} \\
+ & \quad \text{e} \\
+ & \quad \text{Ud} \\
- & \quad \text{id} \\
\end{align*}
\]

Control of 2-Q. converter.
4-Quadrant DC converter

- All combinations of voltage and current

Control of 4-Q converter
Class D Audio Amplifiers

Features
- Power range from 20 to 150 W
  (up to 400 W with application support)
- Excellent power efficiency (≤ 95%)
- Good EMC performance
- Excellent THD (0.01%)
- Symmetrical supply between 15 - 30 V
- Internal oscillator
  - Frequency adjustable between 200 and 600 kHz
  - Can be overridden by an external clock (tracking option)
- Output stage protected against short circuits and overvoltage
- Simple SE and BTL applications
- Few external components
- Asymmetrical supply possible for BTL configurations
  (with application support)
- Powerpath ICs in SOT7F and HSOP24 Power SMD package

3-phase converter

Diagram of a 3-phase converter showing the connections and components involved.
Drive circuits

- All power transistors need a gate/base-driver to:
  - Switch between on- and off-state
  - Turn off at over current
  - Provide galvanic isolation to the control circuitry

- Example of separate driver:
  - 600V and 1200V gate driver in a single IC for MOSFET and IGBTs
  - Multiple Configurations
  - Single high side
  - Half-bridge
  - 3 phase inverter driver
  - Up to +2.0/-2.0A output source/sink current enables fast switching
  - Integrated protection and feedback functions
  - Optional deadtime control
  - Tolerant to negative voltage transient
  - Up to 50V/\text{ns} \text{dV/dt} immunity
  - Optional soft turn-on
  - Uses low cost bootstrap power supply
  - CMOS and LSTTL input compatible

Fully integrated power semiconductors

- Self-containing with built in:
  - Drive circuit
  - Protection circuit
  - Galvanic isolation
  - Power transistor
Passive components

- Inductors
- Capacitors
- Heat sinks

Inductors

- Many types:
  - Ferrite type components
    - For SMPS transformers @ 100 kHz
  - Chokes & Coils & Inductors
    - For EMC supression
  - Toroidal transformers
  - Laminated core transformers
  - Current transformers
  - Noise protection transformers
  - AC voltage stabilizers
Capacitors

- **Electrolytic**
  - For energy storage and filtering
- **Film**
  - For filtering
- **Must be selected with care, can be destroyed by:**
  - Harmonic currents
  - Over voltages
- **Most producers have software design tools available on their home page.**

Heat sinks

- **Extruded**
- **Stacked fin**
- **Water cooled**
- **Integrated in housing**
Power Electronic Design

- All circuits contain capacitive and inductive elements with switches in between.
- Non ideal components contribute to short circuit currents and over voltages that may harm/destroy the circuit.
- Example:

What should look like this: do instead look like this:

- Solution: - Minimize non ideal components

How to improve a circuit

- Minimize length of capacitive cables
- Example:

- Avoid capacitance in inductive circuits
  - Eg. keep primary and secondary winding of a transformer apart.
Integration of passive components
<table>
<thead>
<tr>
<th>1</th>
<th>Principal application areas</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Electrical model</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Thermal equivalent circuit and mounting recommendations</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Series and parallel connections</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Calculate operational life time</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Avoid destroying the capacitor</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>Intermittent operation</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>Calculation examples</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>Operational life time equations</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td><a href="http://www.evox-rifa.com">www.evox-rifa.com</a></td>
<td>13</td>
</tr>
</tbody>
</table>
1 Principal application areas
The main application areas for Evox Rifa electrolytic capacitors are for the
Axial types (PEG):
- Telecom, Lighting, Automotive
- Central switching systems, Electronic ballast, Control units
Can types (PEH):
- Power Electronics Industry
- Drives, Traction, Welding, SMPS, UPS

2 Electrical model
An electric equivalent schema of an electrolytic capacitor can be described as an equivalent series resistance (ESR), equivalent series inductance (ESL), the capacitance (C) and a parallel resistance for the leakage current (R_{leak}).

\[ P_{\text{tot}} = P_{(1)} + P_{(2)} + P_{(3)} + \ldots + P_{(n)} = \]
\[= I_{(1)}^2 \times ESR_{(1)} + I_{(2)}^2 \times ESR_{(2)} + \]
\[+ I_{(3)}^2 \times ESR_{(3)} + \ldots + I_{(n)}^2 \times ESR_{(n)} \]

The power loss causes the temperature to rise in the capacitor. The temperature at the hot-spot (T_h) is decisive for the operational life (L_{OP}) of the capacitor. Increasing T_h leads to decreasing L_{OP}. To calculate T_h the thermal resistance (R_{th}) has to be known. At very high frequencies ESL has to be taken into consideration.

The resonant frequency (f_R) depends on the capacitor. For PEG it can be from 20 kHz up to more than 1 MHz and for PEH it can vary from 1.5 kHz to 150 kHz. If the capacitor is used at a frequency greater than the resonant frequency the capacitor works like an inductor.

3 Thermal equivalent circuit and mounting recommendations
The hot-spot is the hottest point in the capacitor, with temperature T_{th}. Heat will always be transported to the area with lower temperature. From the hot-spot to the ambient there are several ways for the heat to travel. Heat will be transferred through the aluminium foil and the electrolyte. If the capacitor is mounted on a heat-sink some of the heat will go through the heat-sink to the ambient. The total thermal resistance from hot-spot to ambient is called R_{th}. Below are examples of different R_{th} for clip mounted, stud mounted on a heat-sink with a thermal resistance of 2°C/W, and a capacitor stud mounted on a heat-sink with a thermal resistance of 2°C/W with forced air of velocity 2 m/s. This is shown for capacitor type PEH2000O427AM, with ambient temperature of 85°C.

The negative foil is in direct contact with the aluminium case and it is a very good heat conductor. This also means that the aluminium case is the same as the negative, but it should not be used as a connection.

Clip mounted: R_{th} = 3.6°C/W
A correct mounting is necessary if the specified operational life time is to be fulfilled. PEH169 and PEH200 should be mounted upright or inclined down to a horizontal position. The safety vent should be upwards. At a failure, hot conductive electrolyte and vapour can come out from the safety vent, so observe the direction of the vent.

Recommended Not recommended

Having stud mounting with good cooling on a chassis is preferable. When the capacitors are clip mounted there can be an air gap between the capacitor and the heat sink.

It is much easier to stud mount the capacitor compared with clip mounting. Stud mounting with a nylon cap nut gives an isolation voltage of 2.5 to 4 kV depending on the nut. When capacitors are mounted close together, it is important to have a minimum distance of 5 mm between the capacitors in order to have an acceptable air circulation.

It is important to have the right torque for the screw terminal. If the screws are too loose, there can be a bad connection. If the screws are over tightened, there is a risk the thread will be destroyed. The capacitors can’t be mounted hanging in the screw terminals as the lid will break. PEG’s and PEH 430 may be mounted in any position, no accessories are needed. The PEG type should not be squeezed with a plastic strip on the body, this may cause leakage of electrolyte. At applications with high frequencies, the lead should be as short as possible to minimise the inductance and the skin effect. The mounting shown below to the left is not to be recommended. The mounting shown to the right is the preferred.

The PEG should not be mounted near any warm component. High temperatures will shorten the life time and the capacitor can be the limiting part of the construction. For applications with high vibration, as in the automotive industry, the PEG126 is recommended.

4 Series and parallel connections

When using series connection it is important to know the voltage across each capacitor. The tolerances of a capacitor can give a very high voltage on one capacitor while the others are applied to lower voltage. Two 350 V capacitors with tolerances ± 20% are connected in series and over the two capacitors a voltage of 700 V is applied. In the worst case, one capacitor has max. capacitance and the other has min. capacitance. The capacitor with min. value will be exposed for:

\[
U_{\text{cap}} = \frac{U_{\text{applied}} \times \text{Tolerance}_{\text{max}}}{\text{Tolerance}_{\text{max}} + (n-1) \times \text{Tolerance}_{\text{min}}}
\]

\[
= \frac{700 \times 1.2}{1.2 + 0.8} = 420 \text{ VDC}
\]

n = No. of capacitors in series
To obtain correct voltage sharing between the capacitors, it is a good idea to use voltage sharing resistors. The voltage sharing resistor is calculated:

\[
R_{\text{vsr}} = \frac{1000}{0.015 \times C [\mu F]} [\text{k} \Omega]
\]

Example: \( C = 4700 \, \mu F \)
\( R_{\text{vsr}} = 14 \, k\Omega \)

It is important to have a high quality resistor. If the resistor fails, the capacitors will break down. For high reliability the generated power in the resistor should be less than 50% of the rated value. The tolerances of the two resistors should be better or equal to ±5%. Don’t forget the time constant \( \tau \), it takes some time before the voltage is shared.

There are two ways to connect the voltage sharing resistor.

In high current applications it may be necessary to use a parallel connection. Be sure the current distribution is equal in all capacitor branches. At high frequencies, inductances can give different current distribution, as in the first illustration. In the second illustration, the distribution is equal to all capacitors.

Low inductance bus bars can be built to reduce the inductance, down to less than a nH. In principle the negative side must cover the positive side.

5 Calculate operational life time

To calculate the operational life time (\( L_{\text{OP}} \)) you have to know the applied voltage (\( U_{\text{applied}} \)), the current through the capacitor (\( I_{\text{RMS}} \)), ambient temperature (\( T_{a} \)) and thermal resistance (\( R_{\text{th}} \)).

\[
P_{\text{LOSS}} = I_{\text{RMS}}^2 \times \text{ESR}
\]

\[
T_{h} = T_{a} + P_{\text{LOSS}} \times R_{\text{th}}
\]

\( L_{\text{OP}} = f(T_{h}) \)

ESR and \( R_{\text{th}} \)-matrix is available on request. Please contact Evox Rifa sales representative.

First find the ESR value for the right frequency and hot-spot temperature (\( T_{h} \)) in the ESR matrix. Calculate the power loss (\( P_{\text{LOSS}} \)). If the current consists of main frequency and different harmonics, calculate the power loss for each harmonic and add up. The thermal resistance between the winding hot spot and the ambient will be found in the \( R_{\text{th}} \) matrix. Calculate \( T_{h} \) and check if it agrees with the assumption when the ESR was chosen. If not take the new ESR value and make a new calculation. If \( T_{h} \) is known it is easy to calculate \( L_{\text{OP}} \).

\[
L_{\text{OP}} = \frac{85 - T_{h}}{C}
\]

Values for parameter A and C, is given in our catalogue.

The ESR value for electrolytic capacitors depends on the temperature and frequency. Often a value at 20°C and 100 Hz is given.

With the ESR matrix it is possible to calculate the value at other temperatures and frequencies.
**ESR matrix**

Article number PEH200UV4680MB2

Equivalent series resistance factor \( k \) as a function of frequency and winding hot-spot temperature.

\[
ESR (T_h, f) = \frac{ESR (20°C, 100Hz)}{ESR (20°C, 100Hz)}
\]

\[
ESR (20°C, 100Hz) = 15 m\Omega \text{ (Maximum value)}
\]

\[
11 m\Omega \text{ (Typical value)}
\]

---

<table>
<thead>
<tr>
<th>Freq. f kHz</th>
<th>Hot-spot temperature ( T_h ) (°C)</th>
<th>( k )</th>
<th>( ESR (20°C, 100Hz) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>-40</td>
<td>11.6</td>
<td>4.4</td>
</tr>
<tr>
<td>0.10</td>
<td>-40</td>
<td>11.2</td>
<td>4.0</td>
</tr>
<tr>
<td>0.15</td>
<td>-40</td>
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<td>3.8</td>
</tr>
<tr>
<td>0.30</td>
<td>-40</td>
<td>10.9</td>
<td>3.7</td>
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<td>-40</td>
<td>10.9</td>
<td>3.6</td>
</tr>
<tr>
<td>0.60</td>
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<td>3.6</td>
</tr>
<tr>
<td>2.00</td>
<td>-40</td>
<td>10.8</td>
<td>3.6</td>
</tr>
<tr>
<td>5.00</td>
<td>-40</td>
<td>10.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Example:**

Find the ESR value for Hot-spot temperature 70°C and frequency 800 Hz.

Follow the row 0.80 kHz to the column 70°C. The factor will be 0.46. Multiply the ESR value with factor.

\[
ESR (70°C, 800 Hz) = 15 \times 0.46 = 6.9 \text{ m}\Omega \text{ (Maximum value)}
\]

\[
11 \times 0.46 = 5.1 \text{ m}\Omega \text{ (Typical value)}
\]

---

**R\text{th} matrix**

Article number PEH200UV4680MB2

Thermal resistance value as a function of case temperature, \( T_c \), and air speed, \( v \), at ambient temperature \( T_a = 50°C \)

\[
R_{\text{th}}: \text{ thermal resistance between winding hot spot and ambient}
\]

\[
R_{\text{thca}}: \text{ thermal resistance between case and ambient}
\]

---

<table>
<thead>
<tr>
<th>( T_c ) °C</th>
<th>( v = 0.5 \text{m/s} )</th>
<th>( v = 1.0 \text{m/s} )</th>
<th>( v = 1.5 \text{m/s} )</th>
<th>( v = 2.0 \text{m/s} )</th>
<th>( v = 2.5 \text{m/s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R_{\text{th}} ) °C/W</td>
<td>( R_{\text{th}} ) °C/W</td>
<td>( R_{\text{thca}} ) °C/W</td>
<td>( R_{\text{thca}} ) °C/W</td>
<td>( R_{\text{thca}} ) °C/W</td>
</tr>
<tr>
<td>55</td>
<td>2.9</td>
<td>3.5</td>
<td>2.6</td>
<td>3.1</td>
<td>2.3</td>
</tr>
<tr>
<td>60</td>
<td>2.9</td>
<td>3.4</td>
<td>2.6</td>
<td>3.1</td>
<td>2.3</td>
</tr>
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<td>3.4</td>
<td>2.5</td>
<td>3.0</td>
<td>2.3</td>
</tr>
<tr>
<td>80</td>
<td>2.9</td>
<td>3.4</td>
<td>2.5</td>
<td>3.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>

**Example:**

Find the \( R_{\text{th}} \) value for ambient temperature 50°C, case temperature 70°C and air velocity 1.5 m/s.

Follow the row 70°C to the column 1.5 m/s. \( R_{\text{thca}} \) will be 2.3°C and \( R_{\text{th}} \) 2.8°C.

---

Leakage current, \( I_L \), is a direct result of the quality of the dielectric.

The failure rate is given in the catalogue and it is derived from test results.

---

End of life of a capacitor is defined with the following points:

- \( \Delta C / C = \pm 15\% \) for \( U_R \leq 160 \text{ VDC} \)
- \( \Delta C / C = \pm 10\% \) for \( U_R > 160 \text{ VDC} \)
- \( \tan \delta \leq 1.3 \times \text{specified value} \)
- \( I_L < I_{RL} \)
- \( ESR \leq 2 \times \text{ESR initial value} \)
6 Avoid destroying the capacitor

Capacitors can be destroyed if they are exposed to over voltage, for example transients. On the mains there are a lot of transients, it is not a pure sine wave.

To avoid high voltage when connecting the capacitors to voltage it is good to use a soft start. The switch is a semiconductor.

A filter before the rectifier stops some fast transients but not all. If the capacitor is connected to the wrong polarisation it will damage the capacitor very quickly. To avoid wrong polarisation the connections are turned $90^\circ$, i.e. Poka Yoka.

If the current exceeds the rated current it will shorten the life time. Shorter periods of excessive ripple current is okay as long as it's a short duration compared to the thermal time constant, $\tau$. The life time depends on the hot spot temperature. With a temperature sensor or a temperature strip it is possible to measure the temperature rise in the capacitor. The temperature should be measured directly on the aluminium. For PEH169 and 200 it is possible to measure the hot spot temperature with thermo couple inside the capacitor.

**UR** Rated voltage

**US** Surge voltage 1000 cycles with load period 30 sec and no load period 330 sec

**UT** Transient voltage.

The over voltage can also occur when the capacitors are connected to a LC-filter.

The voltage over the capacitor will have an over shot.
7 Intermittent operation PEG126

It is not always relevant to specify an application for continues operation. We are using the following thermal model for intermittent calculations:

The model includes the thermal resistance internally in the capacitor ($R_{thhc}$) and externally between case and ambient ($R_{thca}$). The heat capacitance for the capacitor winding and case is also needed in this dynamic model.

Example:
The thermal parameters and ESR- matrix is available on request, E.g. PEG126KL427BM:

- $R_{thhc} = 7.7 \, \degree\text{C/W}$
- $R_{thca} = 18 \, \degree\text{C/W}$ (without forced air cooling)
- Winding: $C_h = 21 \, \text{J/}\degree\text{C}$
- Case: $C_c = 2.5 \, \text{J/}\degree\text{C}$

Ripple current:
On: 20A, 5kHz during 5 minutes,
Off: No current during 15 minutes (period time: 20 minutes)
Ambient temperature: 93\degree C
No forced air cooling.
ESR=8.7 m\Omega
Power loss: $I_{\text{RMS}}^2 \times \text{ESR}= 3.5\, \text{W}$ (during “on”)
See even chapter 5.

When the thermal parameters is specified and the power loss is calculated, the hot-spot and case temperature can be calculated by computer simulation.

(E.g. PSpice. Transform power loss to DC-current and temperatures to voltages):

Hotspot- ($T_h$) and case temperature ($T_c$), computer simulation:

![Diagram](image)

Specification limits, intermittent operation:
- Up to 95% increased ripple current, compared with specified values at continues operation (at max 25% intermittence)
- Max ripple current, can be applied, at hotspot temperature ($T_h$) up to 135\degree C
- Max ripple current, during 100h, at $T_h \leq 45$ \degree C

Life time calculation:
The life time calculation described in chapter 5, is based on the electrolyte diffusion during continues operation. The diffusion rate is inversely proportional to the calculated $L_{OP}$. Operational life time calculation, at intermittent operation, is than carried out by numeric integration over one temperature cycle:

Operational life ($L_{OP}$) - numerical integration:

\[
L_{OP} = \frac{1}{\left( \text{mean} \left[ 1/ L_{OP} \right] \right)}
\]

where \[ \text{mean} \left[ 1/ L_{OP} \right] = \frac{1}{(\Delta t \times A)} \times \int \frac{1}{2^{\left(\frac{85-T_h}{C}\right)}} \, \text{dt} \]

(integration over 1 temp. cycle \[ \Delta t = 1 \text{ cycle} \])

$L_{OP}$ for the example above: $A=97\, \text{kh}$, $C=11$, $T_h$ in accordance with diagram. Numerical integration $\Rightarrow$ $L_{OP}=12\, \text{kh}$. Max $T_h=135\degree \text{C}$ (OK in accordance to spec. limits.)
8 Calculation examples

The electrolytic capacitor is often used to smooth the voltage after a rectifier.

Needed capacitance to manage a certain level of ripple voltage is

\[
C_{\text{min}} = \frac{2 \times P}{(U_{\text{max}}^2 - U_{\text{min}}^2) \times f_{\text{rectifier}}}
\]

P is the power load in watts.

Remember that this is the minimum required capacitance. It is important to remember the tolerances of the capacitor. During the life time the capacitance will decrease and it will also decrease with low temperatures.

The ripple current from the main and from the load has to be known. First calculate the capacitor voltage charge time.

\[
t_c = \frac{\arccos \left( \frac{U_{\text{min}}}{U_{\text{max}}} \right)}{2 \times \pi \times f_{\text{main}}}
\]

f_{main} is the frequency from the main.

Now it is possible to calculate the capacitor voltage discharge time.

\[
t_{\text{DC}} = \frac{1}{f_{\text{rectifier}}} - t_c
\]

The peak value of the charge current I_C is

\[
I_{\text{peak}} = C \times \frac{dU}{dt_c}
\]

dU is the voltage ripple \((U_{\text{max}} - U_{\text{min}})\).

\[
I_{\text{CRMS}} = \sqrt{I_{\text{peak}}^2 \times t_c \times f_{\text{rectifier}}}
\]

Next the peak and RMS. discharge current can be calculated.

\[
I_{\text{Dpeak}} = C \times \frac{dU}{dt_{\text{DC}}}
\]

\[
I_{\text{DCRMS}} = \sqrt{I_{\text{Dpeak}}^2 \times t_{\text{DC}} \times f_{\text{rectifier}}}
\]

Now the ripple current resulting from the rectification of the AC line can be made.

\[
I_{\text{RMS}} = \sqrt{I_{\text{CRMS}}^2 + I_{\text{DCRMS}}^2}
\]

**Drives**

Continuous voltage: 750 VDC

Ripple currents: 60 A @ 4 kHz
75 A @ 8 kHz
50 A @ 12 kHz
30 A @ 16 kHz
20 A @ 32 kHz

Required capacitance: 7000 µF
Tolerance: -10 to +30%
Life time: 70 000 hours
Maximum ambient temperature: 70°C
Forced air: 2 m/s
Heat sink: 1.0°C/W

To handle the voltage 750 VDC it is necessary to have two capacitors in series. But the tolerances of the capacitors have to be taken into consideration. If the tolerance is ±20%, the worst case gives:

\[
U_{\text{max}} = 750 \times \frac{1.2}{1.2 + 0.8} = 450 \text{ VDC}
\]

Use a 450 V capacitor. If a 4700 µF capacitor is chosen there must be three branches to fulfill the capacitance requirement. PEH200YV447DQB2 is a good selection.

First calculate the ESR values, assume hot-spot temperature to 85°C.

\[
\begin{align*}
\text{ESR} (85°C, 4 \text{ kHz}) &= 13 \times 0.31 = 4.0 \text{ mΩ} \\
\text{ESR} (85°C, 8 \text{ kHz}) &= 13 \times 0.30 = 3.9 \text{ mΩ} \\
\text{ESR} (85°C, 12 \text{ kHz}) &= 13 \times 0.29 = 3.8 \text{ mΩ} \\
\text{ESR} (85°C, 16 \text{ kHz}) &= 13 \times 0.29 = 3.8 \text{ mΩ} \\
\text{ESR} (85°C, 32 \text{ kHz}) &= 13 \times 0.29 = 3.8 \text{ mΩ}
\end{align*}
\]

Calculate the power loss in each capacitor, we have three branches, the capacitor current is a third of the total current.

\[
P_{\text{LOSS}} = \text{ESR}_1 \times I_{\text{RMS1}}^2 + \text{ESR}_2 \times I_{\text{RMS2}}^2 + \text{ESR}_3 \times I_{\text{RMS3}}^2 + \text{ESR}_4 \times I_{\text{RMS4}}^2 + \text{ESR}_5 \times I_{\text{RMS5}}^2 = 0.0040 \times 20.0^2 + 0.0039 \times 25.0^2 + 0.0038 \times 16.7^2 + 0.0038 \times 10.0^2 + 0.0038 \times 6.67^2
\]

\[
= 5.64 \text{ W}
\]

Now it is possible to calculate the hot-spot temperature. The thermal resistance comes from the R_{th}-matrix, thermal resistance of the heat sink is 1.0°C/W and air velocity 2 m/s.

\[
T_h = T_a + P_{\text{LOSS}} \times R_{\text{th}} = 70 + 5.64 \times 1.5 = 78.5°C
\]

The assumption of the hot-spot temperature was 85°C. But for this type of capacitor the ESR doesn’t differ very much at this temperature so there is no need to calculate a new value.
The hot-spot temperature gives the operational life time. PEH200 450 VDC and diameter 75 mm has following LOP equation.

\[
\frac{85-T_h}{12} = 40000 \times 2
\]

\[
85-78.5 = 40000 \times 2 ^{12} = 58.2 \text{ khours}
\]

This solution is far below the specification. It is necessary with four branches.

\[
P_{\text{LOSS}} = ESR_1 \times I_{\text{RMS1}}^2 + ESR_2 \times I_{\text{RMS2}}^2 + ESR_3 \times I_{\text{RMS3}}^2 + ESR_4 \times I_{\text{RMS4}}^2
\]

\[
= 0.0040 \times 15.0^2 + 0.0039 \times 18.8^2 + 0.0038 \times 12.5^2 + 0.0038 \times 7.5^2 + 0.0038 \times 5.0^2 = 3.17 \text{ W}
\]

\[
Th = Ta + P_{\text{LOSS}} \times R_{\text{th}} = 70 + 3.17 \times 1.5 = 74.8^\circ \text{C}
\]

The failure rate per hour is about 5.0 \times 10^{-7}. R(t) is the number of capacitors working.

\[
R(t) = n \times e^{-(\lambda \times t)} \quad \lambda = \text{failure rate}
\]

\[
t = \text{time in hours} \quad n = \text{number of used capacitors}
\]

Assume 80 000 capacitors are used. How many will still work at 57 000 hours?

\[
R (57000h) = 80000 \times e^{-5.0 \times 10^{-7} \times 57000} = 77750
\]

That means 2250 capacitors have failed i.e. 2.8% of the total number.

**Electronic Ballast**

Applied voltage: 420 VDC

Ripple currents:

- 130 mA @ 100 Hz
- 210 mA @ 25 kHz
- 150 mA @ 50 kHz
- 30 mA @ 75 kHz

Required capacitance: 22 \mu F

Tolerance: -10 to +30%

Life time: 50 000 hours

Maximum ambient temperature: 90°C

The capacitor PEG124YH2220Q (450 VDC / 22 \mu F) seems to match the requirements.

First calculate the ESR values, assume hot-spot temperature to 100°C.

- ESR (100°C, 100 Hz) = 2.366 \times 0.94 = 2.22 \Omega
- ESR (100°C, 25 kHz) = 2.366 \times 0.15 = 0.35 \Omega
- ESR (100°C, 50 kHz) = 2.366 \times 0.15 = 0.35 \Omega
- ESR (100°C, 75 kHz) = 2.366 \times 0.15 = 0.35 \Omega

Calculate the power loss in the capacitor.

\[
P_{\text{LOSS}} = ESR_1 \times I_{\text{RMS1}}^2 + ESR_2 \times I_{\text{RMS2}}^2 + ESR_3 \times I_{\text{RMS3}}^2 + ESR_4 \times I_{\text{RMS4}}^2
\]

\[
= 2.22 \times 0.130^2 + 0.35 \times 0.210^2 + 0.35 \times 0.150^2 + 0.35 \times 0.032 = 61 \text{ mW}
\]

Now it is possible to calculate the hot-spot temperature. The thermal resistance comes from the R_{\text{th}}-matrix, assume natural air convection (0.5 m/s).

\[
T_h = T_a + P_{\text{LOSS}} \times R_{\text{th}} = 90 + 0.061 \times 26.2 = 91.6^\circ \text{C}
\]

The assumption of the hot-spot temperature was 100°C. There is no significant difference between ESR (92°C) and ESR (100°C). Recalculation is not needed.

The hot-spot temperature gives the operational life time. PEG124 450 VDC and diameter 20 mm has following LOP equation. LOP in thousand hours.

\[
\frac{85-T_h}{12} = 40000 \times 2
\]

\[
85-74.8 = 40000 \times 2 ^{12} = 72.1 \text{ khours}
\]

This capacitor fulfil the life time requirements.

The failure rate per hour is about 4.0 \times 10^{-7}. R(t) is the number of capacitors working.

\[
R(t) = n \times e^{-(\lambda \times t)} \quad \lambda = \text{failure rate}
\]

\[
t = \text{time in hours} \quad n = \text{number of used capacitors}
\]

Assume 500 000 capacitors are used. How many will still work at 50 000 hours?

\[
R (50000h) = 500000 \times e^{-4.0 \times 10^{-7} \times 50000} = 490000
\]

That means that 1000 capacitors have failed i.e. 2% of the total number.

**Welding**

Continuous voltage: 430 VDC

Ripple currents:

- 15 A @ 100 Hz
- 9 A @ 50 kHz

Required capacitance: 1000 \mu F

Tolerance: ±20%

Life time: 10 000 hours

Maximum ambient temperature: 60°C

Snap-in terminals

Use a 450 VDC capacitor. To handle the ripple currents three 330 \mu F capacitors, PEH430YT3330M2, are used in parallel.
The ESR values are at hot-spot temperature 70°C
ESR (70°C, 100 Hz) = 188 x 0.8 = 150 mΩ
ESR (70°C, 50 kHz) = 188 x 0.15 = 28 mΩ

Calculate the power loss in each capacitor, we have three branches, the capacitor current is a third of the total current.

\[ P_{\text{LOSS}} = ESR_1 \times I_{\text{RMS,1}}^2 + ESR_2 \times I_{\text{RMS,2}}^2 = 0.150 \times 5.0^2 + 0.028 \times 3.0^2 = 4.0 \text{ W} \]

Calculate the hot-spot temperature. The thermal resistance comes from the \( R_{\text{th}} \)-matrix, air velocity 1 m/s.

\[ T_h = T_a + P_{\text{LOSS}} \times R_{\text{th}} = 60 + 4.0 \times 10.7 = 103 \text{°C} \]

It is necessary with four branches. Try with PEH430YT3330M2.

\[ L_{\text{OP}} = 13000 \times 2^{85-T_h \over 12} = 13000 \times 2^{85-103 \over 12} = 4.6 \text{ khours} \]

This solution doesn’t fulfill the requirement of the life time. It is necessary to use more branches or larger capacitors. Forced air is another alternative to reach 10 khours lifetime.

**Automotive**

<table>
<thead>
<tr>
<th>Applied voltage:</th>
<th>14 VDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ripple currents:</td>
<td>3 A @ 20 kHz</td>
</tr>
<tr>
<td>Required capacitance:</td>
<td>600 µF</td>
</tr>
<tr>
<td>Tolerance:</td>
<td>-10 to + 30%</td>
</tr>
<tr>
<td>Life time:</td>
<td>2000 hours</td>
</tr>
<tr>
<td>Maximum ambient temperature:</td>
<td>130°C</td>
</tr>
</tbody>
</table>

Because it is an automotive application it has a high vibration and PEG126 is preferable. We start with PEG126KG360EQL1.

The ESR value is for 140°C and 20 kHz = 0.116 x 0.09 = 11 mΩ

The power loss in the capacitor will be:

\[ P_{\text{LOSS}} = ESR \times I_{\text{RMS}}^2 = 0.0104 \times 3^2 = 94 \text{ mW} \]

Assume no air flow. The thermal resistance will be 34.3°C/W.

\[ T_h = T_a + P_{\text{LOSS}} \times R_{\text{th}} = 130 + 0.094 \times 34.3 = 133 \text{°C} \]

The \( L_{\text{OP}} \) equation for PEG126 (Ø 16 mm) is:

\[ L_{\text{OP}} = 64k \times 2^{85-T_h \over 12} = 64k \times 2^{85-133 \over 12} = 4.0 \text{ khours} \]

The capacitor fulfill the requirements.

**Uninterruptable Power Supply (UPS)**

<table>
<thead>
<tr>
<th>Continuous voltage:</th>
<th>565 VDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ripple currents:</td>
<td>15 A @ 300 Hz</td>
</tr>
<tr>
<td>Required capacitance:</td>
<td>27 A @ 20 kHz</td>
</tr>
<tr>
<td>Tolerance:</td>
<td>1000 µF</td>
</tr>
<tr>
<td>Life time:</td>
<td>-10 to + 30%</td>
</tr>
<tr>
<td>Maximum ambient temperature:</td>
<td>60°C</td>
</tr>
</tbody>
</table>

350 VDC capacitors are used. If two 680 µF capacitors are connected in series, it is necessary to have three branches, for example PEH200UG3680M.

The \( L_{\text{OP}} \) calculation for PEH200 size 50 x 49 mm is

\[ L_{\text{OP}} = 24000 \times 2^{85-T_h \over 12} \]

If the life should be 22 000 hours, maximum hot-spot temperature is

\[ T_h = 85-12 \times \frac{\ln \left( \frac{L_{\text{OP}}}{22000} \right)}{\ln 2} = 85-12 \times \frac{\ln \left( \frac{24000}{22000} \right)}{\ln 2} = 86.5\text{°C} \]

ESR(81°C, 300 Hz) = 0.46 x 0.130 = 60 mΩ
ESR(81°C, 20 kHz) = 0.23 x 0.130 = 30 mΩ

The power loss is

\[ P_{\text{LOSS}} = ESR_1 \times I_{\text{RMS,1}}^2 + ESR_2 \times I_{\text{RMS,2}}^2 = 0.060 \times (15/3)^2 + 0.030 \times (27/3)^2 = 3.9 \text{ W} \]

There are three branches, that is why the currents are divided by three.

Thermal resistance is 6.7°C/W.

\[ T_h = T_a + P_{\text{LOSS}} \times R_{\text{th}} = 60 + 3.9 \times 6.7 = 86\text{°C} \]

The \( L_{\text{OP}} \) calculation is

\[ L_{\text{OP}} = 24000 \times 2^{85-T_h \over 12} = 24000 \times 2^{85-86 \over 12} = 25000 \]

The capacitors fulfill the requirement.
Valve amplifier
DC voltage: 360 VDC
Maximum voltage: 361 VDC
Minimum voltage: 359 VDC
Load current: 250 mA @ 100 Hz

The load power is \( P_{\text{load}} = U \times I = 360 \times 0.25 = 90 \) W

Needed capacitance is
\[
C_{\text{min}} = \frac{2 \times P}{(U_{\text{max}}^2 - U_{\text{min}}^2) \times f} = \frac{2 \times 90}{(361^2 - 359^2) \times 100} = 0.00125 \text{F} = 1250 \mu \text{F}
\]

When the main transformer is unloaded the output can be up to 10% higher. The main power can also increase by 10%. Then the voltage rating of the capacitor must be 360 x 1.1 x 1.1 = 436 VDC. Use a 450 VDC capacitor. PEH200YL4150M is a good selection, rated capacitance is 1500 µF. ESR is less than 43 mΩ at 20°C.

Start to calculate the charge time:
\[
t_C = \frac{\arccos \left( \frac{U_{\text{min}}}{U_{\text{max}}} \right)}{2 \times \pi \times f_{\text{main}}} = \frac{\arccos \left( \frac{359}{361} \right)}{2 \times \pi \times 50} = 335 \mu \text{s}
\]

Discharge time is
\[
t_D = \frac{1}{f_{\text{rectifier}}} - t_C = \frac{1}{100} - 335 \times 10^{-6} = 9665 \mu \text{s}
\]

The peak value of the charge current is
\[
I_{\text{Cpeak}} = C \times \frac{dU}{dt_c} = 1500 \times 10^6 \times \frac{2}{335 \times 10^6} = 8.9 \text{A}
\]

The peak value of the discharge current is
\[
I_{\text{Dpeak}} = \sqrt{I_{\text{Cpeak}}^2 - t_D \times f_{\text{rectifier}}} = \sqrt{8.9^2 \times 335 \times 10^6 \times 100} = 1.6 \text{A}
\]

\[P_{\text{LOSS}} = ESR \times I_{\text{RMS}}^2 = 0.043 \times 1.7^2 = 0.12 \text{W}
\]

In this case the power loss in the capacitor only causes a minor temperature rise above the ambient temperature. \( T_h = T_a \).

9 Operational life time equations

Life time calculation of Rifa electrolytic capacitors

\[
P_{\text{LOSS}} = I_{\text{RMS}}^2 \times ESR
\]

Input: Ambiant temperature = 70°C
Ripple current = 30 A (10 kHz)
\( U_{\text{applied}} = 350 \text{V} \)
ESR (85°C, 10 kHz) = 4.6 mΩ
Thermal resistance \( R_{\text{th}} = 4.3 \text{ °C/W} \)

Calculation:
\[
P_{\text{LOSS}} = 30^2 \times 4.6 \times 10^{-3} = 4.1 \text{W}
\]

Hot spot temp \( T_h = T_a + R_{\text{th}} \times P_{\text{LOSS}} = 70 + 4.3 \times 4.1 = 88 \text{°C}
\]

The assumption of hot-spot temp 85°C was OK!

(There is no significant difference between ESR (88°C) and ESR (85°C)).

Output: Expected Life time \( L_{\text{OP}} = 30000 \times 2 (85-T_h) = 30000 \times 2 \frac{85-88}{12} = 25 \text{ khours}
\]

\( T_h \) and ESR matrixes are available on request. Please contact Evox Rifa sales representative.
On our homepage you can download our CAD application software that automatically calculates the optimum solutions for your power electronics application.
PI-IPM Features:

**Power Module:**
- NPT IGBTs 25A, 1200V
- 10us Short Circuit capability
  - Square RBSOA
  - Low $V_{ce(on)}$ (2.28Vtyp @ 25A, 25°C)
  - Positive $V_{ce(on)}$ temperature coefficient
- Gen III HexFred Technology
  - Low diode $V_f$ (1.76Vtyp @ 25A, 25°C)
  - Soft reverse recovery
- 4mΩ sensing resistors on all phase outputs and DCbus minus rail
  - Thermal coefficient < 50ppm/°C

**Embedded driving board**
- Programmable 40 Mips DSP
- Current sensing feedback from all phases
- Full protection from ground and line to line faults
- UVLO, OVLO on DCbus voltage
- Embedded flyback smps for floating stages (single 15Vdc @ 300mA input required)
- Asynchronous isolated 2.5Mbps serial port for DSP communication and programming
- IEEE standard 1149.1 (JTAG port interface) for program downloading and debugging
- Separated turn on / turn off outputs for IGBTs di/dt control
- Isolated serial port input with strobe signal for quadrature encoders or SPI communication

**Description**
The PIIPM25P12B008 is a fully integrated Intelligent Power Module for high performances Servo Motor Driver applications.
The device core is a state of the art DSP, the TMS320LF2406A at 40 Mips, interfaced with a full set of peripherals designed to handle all analog feedback and control signals needed to correctly manage the power section of the device.

The PI-IPM has been designed and tailored to implement internally all functions needed to close the current loop of a high performances servo motor driver, a basic software is already installed in the DSP and the JTAG connector allows the user to easily develop and download its own proprietary algorithm.
The device comes in the EMp™ package, fully compatible in length, width and height with the popular EconoPack 2 outline.
### Signal pins on RS422 serial port

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Lead Description</th>
<th>Pin number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vin iso</td>
<td>External 5V supply voltage for opto-couplers and line driver supply</td>
<td>6</td>
</tr>
<tr>
<td>GND iso</td>
<td>External 5V supply ground reference for opto-couplers and line driver supply</td>
<td>7</td>
</tr>
<tr>
<td>Tx+</td>
<td>RS422 Transmitter Non inverting Driver Output</td>
<td>1</td>
</tr>
<tr>
<td>Tx-</td>
<td>RS422 Transmitter Inverting Driver Output</td>
<td>2</td>
</tr>
<tr>
<td>Rx+</td>
<td>RS422 Receiver Non inverting Driver Input</td>
<td>4</td>
</tr>
<tr>
<td>Rx-</td>
<td>RS422 Receiver Inverting Driver Input</td>
<td>3</td>
</tr>
<tr>
<td>Enc1 – Hall1 / SpiCK</td>
<td>Incremental Encoder 1 / Hall effect sensor input 1/ SpiCK input (GND iso referenced)</td>
<td>5</td>
</tr>
<tr>
<td>Enc2 – Hall2 / SpiSTE</td>
<td>Incremental Encoder 2 / Hall effect sensor input 2 / SpiSTE input (GND iso referenced)</td>
<td>9</td>
</tr>
<tr>
<td>Strb – Hall3 / SpiRx</td>
<td>Incremental Encoder Strobe / Hall effect sensor input 3 / SpiRx input (GND iso ref.)</td>
<td>10</td>
</tr>
<tr>
<td>SpiTx</td>
<td>SpiTx output (GND iso referenced)</td>
<td>8</td>
</tr>
<tr>
<td>Vin</td>
<td>External 15V supply voltage. Internally referred to DC bus minus pin (DC -)</td>
<td>17-18</td>
</tr>
<tr>
<td>COM</td>
<td>External 15V supply ground reference. This pin is directly connected to DC -</td>
<td>19-20</td>
</tr>
</tbody>
</table>

### Signal pins on IEEE1149.1 JTAG connector

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Lead Description</th>
<th>State</th>
<th>Pin number</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMS</td>
<td>JTAG test mode select</td>
<td>Input</td>
<td>12</td>
</tr>
<tr>
<td>TMS2</td>
<td>JTAG test mode select 2</td>
<td>Input</td>
<td>5-6</td>
</tr>
<tr>
<td>TDI</td>
<td>JTAG test data input</td>
<td>Input</td>
<td>14</td>
</tr>
<tr>
<td>TDO</td>
<td>JTAG test data output</td>
<td>Output</td>
<td>13</td>
</tr>
<tr>
<td>TCK</td>
<td>JTAG test clock. TCK is a 10MHz clock source from the emulation pod. This signal can be used to drive the system test clock.</td>
<td>Input</td>
<td>15</td>
</tr>
<tr>
<td>TRST~</td>
<td>JTAG test reset</td>
<td>Input</td>
<td>11</td>
</tr>
<tr>
<td>EMU0</td>
<td>Emulation pin 0</td>
<td>I/O</td>
<td>9-10</td>
</tr>
<tr>
<td>EMU1/OFF~</td>
<td>Emulation pin 1</td>
<td>I/O</td>
<td>7-8</td>
</tr>
<tr>
<td>PD</td>
<td>Presence detect. Indicates that the emulation cable is connected and that the PI-IPM logic is powered up. PD is tied to the DSP 3.3V supply through a 1k resistor.</td>
<td>Output</td>
<td>1</td>
</tr>
<tr>
<td>TCK_RET</td>
<td>JTAG test clock return. Test clock input to the emulator. Internally short circuited to TCK.</td>
<td>Output</td>
<td>16</td>
</tr>
<tr>
<td>Boot-En</td>
<td>Boot ROM enable. This pin is sampled during DSP reset, pulling it low enables DSP boot ROM (Flash versions only). 47k internal pull up.</td>
<td>Input</td>
<td>17</td>
</tr>
<tr>
<td>COM</td>
<td>External 15V supply ground reference. This pin is directly connected to DC -</td>
<td>N/A</td>
<td>20</td>
</tr>
</tbody>
</table>
Following pins are intended for signal communication between driving board and power module only, though here described for completeness, they are on purpose not available to the user.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Lead Description</th>
<th>Pin number</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC +</td>
<td>DC Bus plus input signal</td>
<td></td>
</tr>
<tr>
<td>DC -</td>
<td>DC Bus minus input signal (internally connected to COM)</td>
<td></td>
</tr>
<tr>
<td>Th +</td>
<td>Thermal sensor positive input</td>
<td></td>
</tr>
<tr>
<td>Th -</td>
<td>Thermal sensor negative input (internally connected to COM)</td>
<td></td>
</tr>
<tr>
<td>Sh +</td>
<td>DC Bus minus series shunt positive input (Kelvin point)</td>
<td></td>
</tr>
<tr>
<td>Sh -</td>
<td>DC Bus minus series shunt negative input (Kelvin point)</td>
<td></td>
</tr>
<tr>
<td>G1/2/3</td>
<td>Gate connections for high side IGBTs</td>
<td></td>
</tr>
<tr>
<td>E1/2/3</td>
<td>Emitter connections for high side IGBTs (Kelvin points)</td>
<td></td>
</tr>
<tr>
<td>R1/2/3 +</td>
<td>Output current sensing resistor positive input (IGBTs emitters 1/2/3 side, Kelvin points)</td>
<td></td>
</tr>
<tr>
<td>R1/2/3 -</td>
<td>Output current sensing resistor negative input (Motor side, Kelvin points)</td>
<td></td>
</tr>
<tr>
<td>G4/5/6</td>
<td>Gate connections for low side IGBTs</td>
<td></td>
</tr>
<tr>
<td>E4/5/6</td>
<td>Emitter connections for low side IGBTs (Kelvin points)</td>
<td></td>
</tr>
</tbody>
</table>

Lateral connectors on embedded driving board

Power Module Frame Pins Mapping
Absolute Maximum Ratings \((T_C=25^\circ C)\)

Absolute Maximum Ratings indicate sustained limits beyond which damage to the device may occur. All voltage parameters are absolute voltages referenced to \(V_{DC-}\), all currents are defined positive into any lead. Thermal Resistance and Power Dissipation ratings are measured at still air conditions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Definition</th>
<th>Min.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{DC})</td>
<td>DC Bus Voltage</td>
<td>0</td>
<td>1000</td>
<td>V</td>
</tr>
<tr>
<td>(V_{CES})</td>
<td>Collector Emitter Voltage</td>
<td>0</td>
<td>1200</td>
<td>V</td>
</tr>
<tr>
<td>(I_{C@100C})</td>
<td>IGBTs continuous collector current ((T_C = 100^\circ C, \text{fig. 1}))</td>
<td>25</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>(I_{C@25C})</td>
<td>IGBTs continuous collector current ((T_C = 25^\circ C, \text{fig 1}))</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(I_{CM})</td>
<td>Pulsed Collector Current ((\text{Fig. 3, Fig. CT.5}))</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(I_{FB@100C})</td>
<td>Diode Continuous Forward Current ((T_C = 100^\circ C))</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(I_{FB@25C})</td>
<td>Diode Continuous Forward Current ((T_C = 25^\circ C))</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(I_{FM})</td>
<td>Diode Maximum Forward Current</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(V_{GE})</td>
<td>Gate to Emitter Voltage</td>
<td>-20</td>
<td>+20</td>
<td>V</td>
</tr>
<tr>
<td>(P_{D@25^\circ C})</td>
<td>Power Dissipation (One transistor)</td>
<td>192</td>
<td></td>
<td>W</td>
</tr>
<tr>
<td>(P_{D@100^\circ C})</td>
<td>Power Dissipation (One transistor, (T_C = 100^\circ C))</td>
<td>77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Inverter**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Definition</th>
<th>Min.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{IN})</td>
<td>Non isolated supply voltage ((\text{DC- referenced}))</td>
<td>-20</td>
<td>20</td>
<td>V</td>
</tr>
<tr>
<td>(V_{IN180})</td>
<td>Isolated supply voltage ((\text{GND iso referenced}))</td>
<td>-7</td>
<td>12</td>
<td>V</td>
</tr>
<tr>
<td>(R_{X})</td>
<td>RS422 Receiver input voltage ((\text{GND iso referenced}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_{A-EDB})</td>
<td>Operating Ambient Temperature Range</td>
<td>-25</td>
<td>+70</td>
<td>^\circ C</td>
</tr>
<tr>
<td>(T_{STG-EDB})</td>
<td>Board Storage Temperature Range</td>
<td>-40</td>
<td>+125</td>
<td>^\circ C</td>
</tr>
<tr>
<td>(V_{ISO-CONT})</td>
<td>Input-Output Continuous Withstand Voltage ((\text{RH} \leq 50%, -40^\circ C \leq T_A \leq 85^\circ C))</td>
<td>AC 800</td>
<td>DC 1000</td>
<td>V</td>
</tr>
<tr>
<td>(V_{ISO-TEMP})</td>
<td>Input-Output Momentary Withstand Voltage ((\text{RH} \leq 50%, t = 1 \text{ min, } T_A = 25^\circ C))</td>
<td>RMS 2500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Embedded Driving Board**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Definition</th>
<th>Min.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MT)</td>
<td>Mounting Torque</td>
<td>3.5</td>
<td></td>
<td>Nm</td>
</tr>
<tr>
<td>(T_J)</td>
<td>Operating Junction Temperature</td>
<td>-40</td>
<td>+150</td>
<td>^\circ C</td>
</tr>
<tr>
<td>(T_{STG})</td>
<td>Storage Temperature Range</td>
<td>-40</td>
<td>+125</td>
<td></td>
</tr>
<tr>
<td>(V_{C-Iso})</td>
<td>Isolation Voltage to Base Copper Plate</td>
<td>-2500</td>
<td>+2500</td>
<td>V</td>
</tr>
</tbody>
</table>
Electrical Characteristics: Inverter
For proper operation the device should be used within the recommended conditions.
\(T_J = 25°C\) (unless otherwise specified)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Definition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
<th>Test Conditions</th>
<th>Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{BR(CE)})</td>
<td>Collector To Emitter Breakdown Voltage</td>
<td>1200</td>
<td></td>
<td></td>
<td>V</td>
<td>(V_{GE} = 0V, I_C = 250\mu A)</td>
<td></td>
</tr>
<tr>
<td>(\Delta V_{BR(CE)} / \Delta T)</td>
<td>Temperature Coeff. of Breakdown Voltage</td>
<td></td>
<td>+1.2</td>
<td></td>
<td>V/ºC</td>
<td>(V_{GE} = 0V, I_C = 1mA (25 - 125 ºC))</td>
<td></td>
</tr>
<tr>
<td>(V_{CE(on)})</td>
<td>Collector To Emitter Saturation Voltage</td>
<td>2.28</td>
<td>2.48</td>
<td></td>
<td>V</td>
<td>(I_C = 25A, V_{GE} = 15V)</td>
<td>5, 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.2</td>
<td>3.65</td>
<td></td>
<td>V</td>
<td>(I_C = 50A, V_{GE} = 15V)</td>
<td>7, 9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.74</td>
<td>3.10</td>
<td></td>
<td>V</td>
<td>(I_C = 25A, V_{GE} = 15V, T_J = 125 °C)</td>
<td>10, 11</td>
</tr>
<tr>
<td>(V_{GEE})</td>
<td>Gate Threshold Voltage</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>V</td>
<td>(V_{CE} = V_{GE}, I_C = 250\mu A)</td>
<td>12</td>
</tr>
<tr>
<td>(\Delta V_{GEE}(T)/\Delta T)</td>
<td>Temp. Coeff. of Threshold Voltage</td>
<td>-1.2</td>
<td></td>
<td></td>
<td>mV/ºC</td>
<td>(V_{CE} = V_{GE}, I_C = 1mA (25 - 125 ºC))</td>
<td></td>
</tr>
<tr>
<td>(g_m)</td>
<td>Forward Transconductance</td>
<td>14.8</td>
<td>16.9</td>
<td>19.0</td>
<td>S</td>
<td>(V_{CE} = 50V, I_C = 25A, PW = 80\mu S)</td>
<td></td>
</tr>
<tr>
<td>(I_{CES})</td>
<td>Zero Gate Voltage Collector Current</td>
<td>250</td>
<td></td>
<td></td>
<td>\mu A</td>
<td>(V_{GE} = 0V, V_{CE} = 1200V)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>325</td>
<td>675</td>
<td></td>
<td>\mu A</td>
<td>(V_{GE} = 0V, V_{CE} = 1200V, T_J = 125 °C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2000</td>
<td></td>
<td></td>
<td>\mu A</td>
<td>(V_{GE} = 0V, V_{CE} = 1200V, T_J = 150 °C)</td>
<td></td>
</tr>
<tr>
<td>(V_{FM})</td>
<td>Diode Forward Voltage Drop</td>
<td>1.76</td>
<td>2.06</td>
<td></td>
<td>V</td>
<td>(I_C = 25A)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.87</td>
<td>2.18</td>
<td></td>
<td>V</td>
<td>(I_C = 25A, T_J = 125 °C)</td>
<td>8</td>
</tr>
<tr>
<td>(I_{RM})</td>
<td>Diode Reverse Leakage Current</td>
<td>20</td>
<td></td>
<td></td>
<td>\mu A</td>
<td>(V_R = 1200V, T_J = 25 °C)</td>
<td></td>
</tr>
<tr>
<td>(I_{GES})</td>
<td>Gate To Emitter Leakage Current</td>
<td>±100</td>
<td></td>
<td></td>
<td>nA</td>
<td>(V_{GE} \pm 20V)</td>
<td></td>
</tr>
<tr>
<td>(R_{1/2/3})</td>
<td>Sensing Resistors</td>
<td>3.96</td>
<td>4</td>
<td>4.04</td>
<td>mΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(R_{sh})</td>
<td>DC bus minus series shunt resistor</td>
<td>3.96</td>
<td>4</td>
<td>4.04</td>
<td>mΩ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Switching Characteristics: Inverter

For proper operation the device should be used within the recommended conditions. \( T_J = 25^\circ C \) (unless otherwise specified)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Definition</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
<th>Test Conditions</th>
<th>Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_g )</td>
<td>Total Gate Charge (turn on)</td>
<td>169</td>
<td>254</td>
<td></td>
<td>nC</td>
<td>( I_C = 25A )</td>
<td>23</td>
</tr>
<tr>
<td>( Q_{ge} )</td>
<td>Gate – Emitter Charge (turn on)</td>
<td>19</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q_{gc} )</td>
<td>Gate – Collector Charge (turn on)</td>
<td>82</td>
<td>123</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_{on} )</td>
<td>Turn on Switching Loss</td>
<td>1.9</td>
<td>3.6</td>
<td></td>
<td>mJ</td>
<td>( I_C = 25A, V_{CC} = 600V, T_J = 25^\circ C )</td>
<td>CT4</td>
</tr>
<tr>
<td>( E_{off} )</td>
<td>Turn off Switching Loss</td>
<td>1.3</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_{t} )</td>
<td>Total Switching Loss</td>
<td>3.2</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_{on} )</td>
<td>Turn on Switching Loss</td>
<td>2.7</td>
<td>4.6</td>
<td></td>
<td>mJ</td>
<td>( I_C = 25A, V_{CC} = 600V, T_J = 125^\circ C )</td>
<td>13, 15</td>
</tr>
<tr>
<td>( E_{off} )</td>
<td>Turn off Switching Loss</td>
<td>2.0</td>
<td>2.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_{t} )</td>
<td>Total Switching Loss</td>
<td>4.7</td>
<td>6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t_d )</td>
<td>Turn on delay time</td>
<td>192</td>
<td>210</td>
<td></td>
<td>ns</td>
<td>( I_C = 25A, V_{CC} = 600V, T_J = 125^\circ C )</td>
<td>14, 16</td>
</tr>
<tr>
<td>( T_r )</td>
<td>Rise time</td>
<td>33</td>
<td>49</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t_d )</td>
<td>Turn off delay time</td>
<td>213</td>
<td>227</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_f )</td>
<td>Fall time</td>
<td>210</td>
<td>379</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_{iss} )</td>
<td>Input Capacitance</td>
<td>2200</td>
<td></td>
<td></td>
<td>PF</td>
<td>( V_{CC} = 30V )</td>
<td></td>
</tr>
<tr>
<td>( C_{oss} )</td>
<td>Output Capacitance</td>
<td>210</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_{rss} )</td>
<td>Reverse Transfer Capacitance</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RBSOA</td>
<td>Reverse Bias Safe Operating Area</td>
<td>FULL SQUARE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCOSA</td>
<td>Short Circuit Safe Operating Area</td>
<td>10</td>
<td></td>
<td></td>
<td>( \mu s )</td>
<td>( T_J = 150^\circ C, I_C = 100A, V_{GE} = 15V ) to 0V</td>
<td>CT3</td>
</tr>
<tr>
<td>ERER</td>
<td>Diode reverse recovery energy</td>
<td>1820</td>
<td>2400</td>
<td></td>
<td>( \mu J )</td>
<td>( T_J = 125^\circ C )</td>
<td></td>
</tr>
<tr>
<td>( T_{rr} )</td>
<td>Diode reverse recovery time</td>
<td>300</td>
<td></td>
<td></td>
<td>( \mu s )</td>
<td>( I_C = 25A, V_{CC} = 600V ),</td>
<td>17, 18, 19, 20</td>
</tr>
<tr>
<td>( I_{rr} )</td>
<td>Peak reverse recovery current</td>
<td>25</td>
<td>32</td>
<td></td>
<td>A</td>
<td>( V_{GE} = 15V, R_G = 20\Omega, L = 200\mu H )</td>
<td>21, CT4</td>
</tr>
<tr>
<td>( R_{thJC,T} )</td>
<td>Each IGBT to copper plate thermal resistance</td>
<td>0.65</td>
<td></td>
<td></td>
<td>( ^\circ C/W )</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>( R_{thJC,D} )</td>
<td>Each Diode to copper plate thermal resistance</td>
<td>1.05</td>
<td></td>
<td></td>
<td>( ^\circ C/W )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R_{thCP,H} )</td>
<td>Module copper plate to heat sink thermal resistance. Silicon grease applied = 0.1mm</td>
<td>0.03</td>
<td></td>
<td></td>
<td>( ^\circ C/W )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pdiss</td>
<td>Total Dissipated Power</td>
<td>52</td>
<td></td>
<td></td>
<td>W</td>
<td>( I_C = 3.5A, V_{OC} = 530V, fsw = 8kHz, T_C = 55^\circ C )</td>
<td>PD1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PD2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>114</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PD3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>102</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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Electrical Characteristics: Embedded Driving Board (EDB) communication ports
For proper operation the device should be used within the recommended conditions. 
Vin = 15V, Vin-iso = 5V, T_A = 0 to 55C, T_C = 75C  (unless otherwise specified)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Definition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
<th>Test Conditions</th>
<th>Conn.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vin</td>
<td>EDB Input supply Voltage</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isupp</td>
<td>EDB input Supply Current with EEprom not programmed</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>mA</td>
<td>V_OC = 0V, fPWM = 8kHz(*)</td>
<td></td>
</tr>
<tr>
<td>Isupp</td>
<td>EDB Input Supply Current</td>
<td>126</td>
<td>139</td>
<td>151</td>
<td>mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIN iso</td>
<td>EDB isolated supply voltage</td>
<td>4.5</td>
<td>5</td>
<td>5.5</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iq. iso</td>
<td>EDB isolated quiescent supply current</td>
<td>9</td>
<td>20</td>
<td>-</td>
<td>mA</td>
<td>Rx+ = +5V, Rx- = 0V, Hall1/2/3 = open</td>
<td></td>
</tr>
<tr>
<td>Isupp. iso</td>
<td>EDB isolated supply current</td>
<td>24</td>
<td>29</td>
<td>34</td>
<td>mA</td>
<td>Hall1/2/3 low</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>37</td>
<td>48</td>
<td>59</td>
<td>mA</td>
<td>Hall1/2/3 low</td>
<td></td>
</tr>
<tr>
<td>VDD-TX</td>
<td>Differential Driver Output Voltage</td>
<td>2</td>
<td></td>
<td></td>
<td>V</td>
<td>R_Load = 120 Ω</td>
<td></td>
</tr>
<tr>
<td>VCO-TX</td>
<td>Driver Common mode output voltage</td>
<td>3</td>
<td></td>
<td></td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VDI-RX</td>
<td>Receiver Input Differential Threshold Voltage</td>
<td>-0.2</td>
<td>0.2</td>
<td></td>
<td>V</td>
<td>-7V ≤ V_CM ≤ +12V</td>
<td></td>
</tr>
<tr>
<td>RIN-RX</td>
<td>Receiver Input Resistance</td>
<td>120</td>
<td></td>
<td></td>
<td>Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fMAX</td>
<td>RS422 maximum data rate</td>
<td>2.5</td>
<td></td>
<td></td>
<td>Mbps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venc-high / Vhall-high</td>
<td>Logic High Input Voltage</td>
<td>3.6</td>
<td></td>
<td></td>
<td>V</td>
<td>Enc1 / Hall1 Enc2 / Hall2 Strb / Hall3 input pins</td>
<td></td>
</tr>
<tr>
<td>Venc-low / Vhall-low</td>
<td>Logic Low Input Voltage</td>
<td>2</td>
<td></td>
<td></td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ienc-low / Ihall-low</td>
<td>Logic Low Input Current</td>
<td>-5.2</td>
<td></td>
<td></td>
<td>mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JTAG</td>
<td>JTAG interface pins</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VPD</td>
<td>Presence detect voltage</td>
<td>3.2</td>
<td>3.3</td>
<td>3.4</td>
<td>V</td>
<td>I_PD = -100μA</td>
<td>JTAG</td>
</tr>
<tr>
<td>VBoot En</td>
<td>Boot ROM enable input voltage</td>
<td>0.5</td>
<td></td>
<td></td>
<td>V</td>
<td>Active low</td>
<td>JTAG</td>
</tr>
<tr>
<td>IBoot En</td>
<td>Boot ROM enable input current</td>
<td>-100</td>
<td></td>
<td></td>
<td>μA</td>
<td></td>
<td>JTAG</td>
</tr>
</tbody>
</table>

* these values are obtained with internal DSP clock, EVA, EVB, SCI peripherals enabled at 40MHz, A/D peripheral at 20MHz and 50% PWM duty cycle on all legs.
AC Electrical Characteristics: Embedded Driving Board (EDB)

DSP pins mapping

For proper operation the device should be used within the recommended conditions.

Vin = 15V, Vin-iso = 5V, TA = 0 to 55°C, TC = 75°C (unless otherwise specified)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Definition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
<th>Test Conditions</th>
<th>DSP name ; pin N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDCPAN</td>
<td>DC bus voltage feedback partition coefficient</td>
<td>2.39</td>
<td>2.44</td>
<td>2.49</td>
<td>mV/V</td>
<td></td>
<td>ADCin03;72</td>
</tr>
<tr>
<td>VDCpole</td>
<td>DC bus voltage feedback filter pole</td>
<td>950</td>
<td>1000</td>
<td>1050</td>
<td>Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VDC-MAX</td>
<td>Maximum DC bus voltage read</td>
<td>1309</td>
<td></td>
<td></td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VDC-ON</td>
<td>DC bus voltage over-voltage threshold</td>
<td>870</td>
<td>920</td>
<td>970</td>
<td>V</td>
<td></td>
<td>PDPINTA;6</td>
</tr>
<tr>
<td>VTH25C</td>
<td>Thermal sensor voltage feedback at 25 ºC (Fig. TF1)</td>
<td>2.65</td>
<td>2.75</td>
<td>2.85</td>
<td>V</td>
<td></td>
<td>ADCin04;70</td>
</tr>
<tr>
<td>VTH100C</td>
<td>Thermal sensor voltage feedback at 100 ºC (Fig. TF1)</td>
<td>1.04</td>
<td>1.09</td>
<td>1.14</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vin-gain</td>
<td>Input voltage feedback partition coefficient</td>
<td>125</td>
<td>128</td>
<td>131</td>
<td>mV/V</td>
<td></td>
<td>ADCin05;69</td>
</tr>
<tr>
<td>Vin-pole</td>
<td>Input voltage feedback filter pole</td>
<td>1600</td>
<td>1700</td>
<td>1800</td>
<td>Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iph-GAIN</td>
<td>Current feedback gain</td>
<td>33.2</td>
<td>33.8</td>
<td>34.4</td>
<td>mV/A</td>
<td></td>
<td>ADCin00: 79</td>
</tr>
<tr>
<td>Iph-pole</td>
<td>Current feedback filter pole</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
<td>kHz</td>
<td></td>
<td>ADCin01: 77</td>
</tr>
<tr>
<td>Iph-MAX</td>
<td>Maximum Current feedback read</td>
<td>47</td>
<td></td>
<td></td>
<td>A</td>
<td></td>
<td>ADCin02: 74</td>
</tr>
<tr>
<td>Iph-MIN</td>
<td>Minimum Current feedback read</td>
<td>-47</td>
<td></td>
<td></td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iph-LAT</td>
<td>Current feedback signal delay</td>
<td>12</td>
<td></td>
<td></td>
<td>µs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iph-Zero</td>
<td>Zero current input voltage level</td>
<td>1.64</td>
<td>1.67</td>
<td>1.70</td>
<td>V</td>
<td></td>
<td>PDPINTA;6</td>
</tr>
<tr>
<td>ISC</td>
<td>Short Circuit Threshold Current</td>
<td>110</td>
<td>128</td>
<td>146</td>
<td>A</td>
<td>all phases</td>
<td></td>
</tr>
<tr>
<td>ISC-Delay</td>
<td>Short Circuit detection delay time</td>
<td>3</td>
<td>6</td>
<td></td>
<td>µs</td>
<td>all phases</td>
<td></td>
</tr>
<tr>
<td>DCOC</td>
<td>DC bus minus over-current level</td>
<td>130</td>
<td>140</td>
<td>150</td>
<td>A</td>
<td>DC bus minus</td>
<td>PDPINTA;6</td>
</tr>
<tr>
<td>DCOCpole</td>
<td>DC bus minus over-current filter pole</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>kHz</td>
<td>DC bus minus</td>
<td></td>
</tr>
<tr>
<td>WD</td>
<td>External watchdog timeout (see also RS~ signal)</td>
<td>0.9</td>
<td>1.6</td>
<td>2.5</td>
<td>Sec</td>
<td>WD;85</td>
<td></td>
</tr>
<tr>
<td>COM</td>
<td>DSP Ground</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3V</td>
<td>DSP 3.3V supply</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>floating</td>
<td>The following pins are left unconnected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>42, 44, 51, 88,</td>
</tr>
<tr>
<td>Ref3.3V</td>
<td>3.3V reference voltage</td>
<td>3.33</td>
<td></td>
<td></td>
<td>V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates active low signals
### Other DSP pins mapping

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Signal Definition</th>
<th>DSP pin name ;pin N</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM1</td>
<td>OUT 1 high side IGBT gate drive signal</td>
<td>PWM1;39</td>
<td>DSP Event Manager A output</td>
</tr>
<tr>
<td>PWM2</td>
<td>OUT 1 low side IGBT gate drive signal</td>
<td>PWM2;37</td>
<td>DSP Event Manager A output</td>
</tr>
<tr>
<td>PWM3</td>
<td>OUT 2 high side IGBT gate drive signal</td>
<td>PWM3;36</td>
<td>DSP Event Manager A output</td>
</tr>
<tr>
<td>PWM4</td>
<td>OUT 2 low side IGBT gate drive signal</td>
<td>PWM4;33</td>
<td>DSP Event Manager A output</td>
</tr>
<tr>
<td>PWM5</td>
<td>OUT 3 high side IGBT gate drive signal</td>
<td>PWM5;31</td>
<td>DSP Event Manager A output</td>
</tr>
<tr>
<td>PWM6</td>
<td>OUT 3 low side IGBT gate drive signal</td>
<td>PWM6;28</td>
<td>DSP Event Manager A output</td>
</tr>
<tr>
<td>Enc1–Hall1 / SpiCK</td>
<td>Incremental Encoder 1 / Hall effect sensor input 1 / SpiCK input (GND iso referenced)</td>
<td>SPICK;24 QEP1;57</td>
<td>Optically isolated input</td>
</tr>
<tr>
<td>Enc2– Hall2 / SpiSTE</td>
<td>Incremental Encoder 2 / Hall effect sensor input 2 / SpiSTE input (GND iso referenced)</td>
<td>SPISTE;–23 QEP2; 55</td>
<td>Optically isolated input</td>
</tr>
<tr>
<td>Strb– Hall3 / SpiRx</td>
<td>Incremental Encoder Strobe / Hall effect sensor input 3 / SpiSIMO input (GND iso ref.)</td>
<td>SPISIMO;21 CAP3; 52</td>
<td>Optically isolated input</td>
</tr>
<tr>
<td>SpiTx</td>
<td>SpiSOMI output (GND iso referenced)</td>
<td>SPISSOMI;22</td>
<td>Optically isolated input</td>
</tr>
<tr>
<td>Ref3.3V</td>
<td>3.3V reference voltage</td>
<td>Vrefh;82</td>
<td>3.33V reference voltage for ADC converter</td>
</tr>
<tr>
<td>5V supp.</td>
<td>Flash programming voltage pin</td>
<td>Vccp;40</td>
<td>Supplied by the embedded flyback regulator</td>
</tr>
<tr>
<td>Boot En~</td>
<td>Boot ROM enable signal</td>
<td>BOOT_EN~;86</td>
<td>See also EDB electrical characteristics</td>
</tr>
<tr>
<td>Tx</td>
<td>SCI transmit data</td>
<td>SCITXD;17 CANTX ; 50</td>
<td>Drives Tx+ and Tx- through an opto-isolator and a line driver</td>
</tr>
<tr>
<td>Rx</td>
<td>SCI receive data</td>
<td>SCIRX ; 18 CANRX ; 49</td>
<td>Driven by Rx+ and Rx- through an opto-isolator and a line driver</td>
</tr>
<tr>
<td>LFAULT</td>
<td>System general fault input (latched)</td>
<td>IOPF6;92</td>
<td>Activated by short circuits on output phases and DC bus minus and by DC bus over-voltage comparator</td>
</tr>
<tr>
<td>LFAULT reset</td>
<td>System general fault output reset signal</td>
<td>IOPF5;89</td>
<td>LFAULT Reset signal, to be activated via software after a fault or system boot.</td>
</tr>
<tr>
<td>FAULT~</td>
<td>System general fault input (not latched)</td>
<td>PDPINTA~;6</td>
<td>Activated by short circuits on output phases and DC bus minus and by DC bus over-voltage comparator</td>
</tr>
<tr>
<td>RS~</td>
<td>DSP reset input signal (see also WD signal)</td>
<td>RS~;93</td>
<td>Forces a DSP reset if WD signal holds too long (see also EDB electrical char.)</td>
</tr>
<tr>
<td>Xtal1</td>
<td>PLL oscillator input pin</td>
<td>XTAL1;87</td>
<td>A 10Mhz oscillator at 100ppm frequency stability feeds this pin.</td>
</tr>
<tr>
<td>PLLF1</td>
<td>PLL filter input 1</td>
<td>PLLF;9</td>
<td>PLL filter for 40Mhz DSP clock frequency</td>
</tr>
<tr>
<td>PLLF2</td>
<td>PLL filter input 2</td>
<td>PLLF2;8</td>
<td>PLL filter for 40Mhz DSP clock frequency</td>
</tr>
<tr>
<td>PDPINTB</td>
<td>External protection interrupt for EVB</td>
<td>PDPINTB~;95</td>
<td>Not used pull up 4.7K to 3.3V</td>
</tr>
</tbody>
</table>

~ indicates active low signals
General Description

The PI-IPM is a new generation of Intelligent Power Module designed specifically to implement itself a complete motor driver system. The device contains all peripherals needed to control a six IGBTs inverter, including voltage, temperature and current output sensing, completely interfaced with a 40Mips DSP, the TMS320LF2406A from Texas Instruments. All communication between the DSP and the local host, including DSP software installing and debugging, is realized through an asynchronous isolated serial port (SCI), an isolated port for incremental encoder inputs or synchronous serial port communication (SPI) is also provided making this module a complete user programmable solution connected to the system only through a serial link cable.

System Description

The PI-IPM is realized in two distinct parts: the Power Module “EMP” and the Embedded Driving Board “EDB,” these two elements assembled together constitute the complete device with all performances described in the following.

The complete block schematic showing all functions implemented in the product is represented on the System Block Schematic on page 1. The new module concept includes everything depicted within the dotted line, the EMP power module includes IGBTs, Diodes and Sensing Resistors while all remaining electronics is assembled on the EDB that is fitted on the top of it as a cover with also mechanical protective functions.

Connections between the two parts are realized through a single-in-line connector and the EDB only, without disassembling the power module from the system mechanic, can be easily substituted “at the factory” for an upgrade, a system configuration change (different control architecture) or a board replacement. Also software upgrades are possible but this does not even require any hardware changes thanks to the DSP programmability through the serial or JTAG ports.

THE “EMP™” POWER MODULE

This module contains six IGBTs + HexFreds Diodes in a standard inverter configuration. IGBTs used are the new NPT 1200V-25A (current rating measured @ 100C), generation V from International Rectifier; the HexFred diodes have been designed specifically as pair elements for these power transistors. Thanks to the new design and technologic realization, this gen V devices do not need any negative gate voltage for their complete turn off and the tail effect is also substantially reduced compared to competitive devices of the same family. This feature simplifies the gate driving stage that will be described in a dedicated chapter. Another not standard feature in this type of power modules is the presence of sensing resistors in the three output phases, for precise motor current sensing and short circuit protections, as well as another resistor of the same value in the DC bus minus line, needed only for device protections purposes. A complete schematic of the EMP module is shown on page 1 where sensing resistors have been clearly evidenced, a thermal sensor is also embedded and directly coupled with the DSP inputs.

The package chosen is mechanically compatible with the well known EconoPack outline, also the height of the plastic cylindrical nuts for the external PCB positioned on its top is the same, so that, with the only re-layout of the main motherboard, this module can fit into the same mechanical fixings of the standard Econo II package thus speeding up the device evaluation in an already existing driver.

An important feature of this new device is the presence of Kelvin points for all feedback and command signals between the board and the module with the advantage of having all emitter and resistor sensing independent from the power path. The final benefit is that all low power signal from/to the controlling board are unaffected by parasitic inductances or resistances inevitably present in the module power layout.
The new package outline is show on page 4, all signal and power pins are clearly listed, note that because of high current spikes on those inputs the DC bus power pins are doubled in size comparing to the other power pins. Module technology uses the standard and well know DBC: over a thick Copper base an allumina (Al₂O₃) substrate with a 300μm copper foil on both side is placed and IGBTs and Diodes dies are directly soldered, through screen printing process. These dies are then bonded with a 15 mils aluminum wire for power and signal connections. All components are then completely covered by a silicone gel with mechanical protection and electrical isolation purposes.

**THE “EDB” EMBEDDED DRIVING BOARD**

This is the core of the device intelligence, all control and driving functions are implemented at this level, the board finds its natural placement as a cover of the module itself and has a double function of mechanical cover and intelligent interface. DSP and all other electronics are here assembled; figure on page 2 shows the board schematic and all connection pins.

Looking at the schematic, all diamond shaped pins are signal connections, some belonging to the RS422 port interface and some to the IEEE 1149.1 (JTAG) connector. All other pins are used for communication between the board and the module, they are positioned laterally in the board and the module doesn’t have any pins in the middle of its body.

From the top left, in anti-clockwise direction we identify the following blocks that will be then described in details:

1. DSP and opto isolated serial and JTAG ports
2. Flyback Power Supply
3. Current Sensing interfaces, over-current protections and signal conditioning
4. Gate drivers
5. DC bus and Input voltage feedback

**1. DSP and opto isolated serial and JTAG ports.**

The DSP used in this application is the new TMS320LF2406A from TI, it is a improvement of the well known in the motor driver market “F240” used in many motor driver applications. If we compare this new device with the predecessor, the new DSP has some added features that let the software designer significantly improve the system control performances, the following table shows a list of relevant data, for all other information please refer to the related device datasheet. To be noted is the increased number of instruction per second, (40MIPS) and of I/O pins, the availability of a boot ROM and a CAN, a much faster ADC and the reduced supply voltage from 5V down to 3.3V, to follow the global trend for this type of products. The choice of the DSP has been done looking at the high number of applications already existing in the market using devices of this family, however it is clear that the same kind of approach could be followed using products from different suppliers to let the customer work on its preferred and well known platform.

**TMS320LF2406A vs TMS320F240**

<table>
<thead>
<tr>
<th></th>
<th>TMS320LF2406A</th>
<th>TMS320F240</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIPS</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>RAM</td>
<td>2.5Kw</td>
<td>5.4Kw</td>
</tr>
<tr>
<td>Flash</td>
<td>32Kw</td>
<td>16Kw</td>
</tr>
<tr>
<td>ROM</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Boot ROM</td>
<td>2.56w</td>
<td>—</td>
</tr>
<tr>
<td>Ext. Memory I/F</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Event manager</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>• GP timers</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>• CMP/PWM</td>
<td>10/16</td>
<td>9/12</td>
</tr>
<tr>
<td>• CAP/QEP</td>
<td>6/4</td>
<td>4/2</td>
</tr>
<tr>
<td>Watchdog timer</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>10-bit ADC</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>• Channels</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>• Conv. time (min)</td>
<td>500ns</td>
<td>6.6μs</td>
</tr>
<tr>
<td>SPI</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>SCI</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>CAN</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Digital I/O pins</td>
<td>37</td>
<td>28</td>
</tr>
<tr>
<td>Voltage range</td>
<td>3.3V</td>
<td>5 V</td>
</tr>
</tbody>
</table>
The “2406A” has three different serial interfaces available: SCI, SPI, and CAN bus. In the PI-IPM25P12B008 communication is made through the asynchronous port (SCI) while four other opto-isolated lines can be used for the SPI or for the hall effect sensor interface. Maximum bit rate for this asynchronous serial port is 2.5Mbps while the SPI (synchronous) could reach 10Mbps. The choice of the SCI has been taken for easy interfacing with a standard computer serial port, the only component needed is a line driver to adapt the RS232 voltage standard with the RS422 at 3.3V used on this application.

In a standard Brushless motor application usually 1Mbps are far enough to transmit all information needed for the torque reference updates and other fault and feedback signals at a maximum frame rate of 10kHz (100bits/frame), in this way the on-board line driver let the application use long connecting wires between the host and the module, leaving the user the possibility of having the PI-IPM displaced near the motor, e.g. in its connecting box, thus avoiding long ad noisy three phase cables between driver and load.

The JTAG port is the standard one, neither isolation nor signal conditioning are provided here and all signal, except the Tck-ret, are directly connected from the related DSP pins to the connector; however, due to the limited board space, the connector used in not the standard 14 pins at two rows header, then an adaptor has to be realized to connect it to the JTAG adapter interface provided by Texas Instruments.

Last but not least is the ADC speed and load characteristic: as the table shows the conversion time is 500ns, in fact the 2406A DSP has a single ADC handling, in time sharing, all 16 inputs, then, using 6 inputs, the total conversion time, which is a fixed delay to wait for before having all data updated, is around 3.0µs.

2. Flyback Power Supply

A flyback power supply for the floating stages is provided in the EDB. As the block schematic on page 2 shows, we have three 15V outputs for the floating stages, isolated from each other at 1.5kV minimum, and a single 5V and 3.3V output.

The 5V supplies all low voltage electronics and a 3.3V linear regulator is used to feed the DSP and some analog and logic interfaces to it. This 5V and 3.3V are directly referred to the DC bus minus, so that all control circuitry is alternately at one of the input lines potential, isolation is provided at the DSP serial link level, then avoiding all delays due to opto couplers insertion between DSP and control logic. Note that also the required 15V input voltage is referred to the same DC bus minus and directly supplies the low side gate drivers stages, the user should pay some attention on how this supply line is realized in his application. Just for completeness, the following figure gives a possible solution to that that doesn’t impact heavily on the user application.

![Examples of power supply for PI-IPM 15V and 5V iso inputs](image)

Normally a 5V power supply is already present, for displays, electronics and micro processor, the same 5V could be used for the 5V iso supply of opto-couplers and line driver, the 15V could be realized as an added winding in the secondary side of the flyback transformer, the only care that should be taken is in keeping its isolation from the above mentioned 5V at the required level (at least 1.5kV).

To avoid noise problems in the measuring lines due to the commutating electronics during normal functioning of the system, references are kept separated. A 5V linear regulator, directly supplied from the 15V input, is used to provide the reference voltage to the current sensing amplifying and conditioning components while a precise op-amp, configured as a voltage follower, acts as a buffer of the partition at 3.30V created down the 5V reference. This 3.30V is used also as reference for the DSP A/D converter. It has to be noted that in the schematic we are using the...
same linear regulator as a starting point for all reference voltages. In fact if the 5V linear regulator drifts in temperature or time, then all references (even the 3.30V being this a simple partitioning) follow in track and still keep the overall chain precision. The trimming is then done only once, in a single point of the measuring chain, that is the conditioning op-amp collecting the current sensing ICs signal as will then be described in the following chapter.

3. Current sensing interfaces, over-current protections and signal conditioning.

This block is the real critical point of the system. Current measuring performances directly impact on motor control performances in a servo application: errors in current evaluation, delay in its measuring chain or poor overall precision of the system, such as scarce references or lower number of significant A/D bits, inevitably results in unwanted trembling and unnatural noise coming from the motor while running at lower speed or at blocked shaft conditions.

In the PI-IPM25P12B008 the current sensing function is done through three sensing resistors dropout measurement, one on each output phase, with the benefit of a lower area and somewhat a lower cost compared to the well-known Hall effect devices. This solution has the added value of having the shunts element embedded in the power module with all Kelvin connections available, avoiding any noise due to long routing of power paths.

As the block schematic on page 2 shows, the voltage across each sensing resistor is applied, through an anti-aliasing 400kHz filter, at the input of a current sense IC and then to a signal conditioning circuit.

Though the block schematic here shows an Op-Amp plus an external passive filter this is simply realized implementing a VCVS cell (i.e. a Constant Gain or Sallen – Key cell) configured so that the offset and gain is easily trimmed by three on board resistors. The filter implemented is a second order Bessel with 5.5kHz pole frequency, the reason for this is that this type of polynomials are calculated with the aim of having a constant group delay within the pass-band frequencies, thus giving the minimum waveform distortion to the output signal up to almost twice the filter pole. In other words we could also say that the group delay of the signal chain from the sensing resistor up to the ADC input of the DSP is constant from 0 to 5.5kHz.

Signal outputted from the overall chain has a 0 to +3.30V dynamic, with a sensing resistor of 4mohms the input measured current range is +/-50A then we have a situation as follows:

\[
\begin{align*}
    -50A &= 0.0V \\
    0.00A &= 1.65V \\
    +50A &= 3.30V
\end{align*}
\]

Summing up our current measurements performances are shown in the following table:

<table>
<thead>
<tr>
<th>PI-IPM Current sensing chain typical performances</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>current range</td>
<td>+/- 50</td>
<td>A</td>
</tr>
<tr>
<td>Gain and Offset precision</td>
<td>+/- 1.8</td>
<td>%</td>
</tr>
<tr>
<td>bandwidth</td>
<td>5.5</td>
<td>kHz</td>
</tr>
<tr>
<td>latency time</td>
<td>10</td>
<td>µs</td>
</tr>
</tbody>
</table>

The “2406A” DSP has a 10bit ADC, consequently the PI-IPM25P12B008 has a minimum appreciable current step of approximately:

\[
LSB = \frac{2^{10}}{2} = 0.0976A
\]

that is: 1LSB ≈ 98mA

The over current protection is provided also through the current sensing ICs, the related fault signal is activated when a 250mV voltage across sensing pins is detected, this means an over-current detection level of approximately 25%. The delay of this line is around 3µs, fast enough to let the DSP react within the 10µs IGBTs short circuit rating, thus providing full device protection for any phase-to-ground and phase-to-
phase short circuits. The only failure not covered in this way is the shoot-through, where high current levels cannot be detected from outside the module rather internally between two IGBTs of the same leg. In this case the protection is implemented by means of the fourth sensing element, with the same resistive value of the other shunts present in the power module, inserted in series to the DC bus minus. The related dropout voltage is then filtered by a 15kHz passive filter to avoid false fault detections due to unwanted induced voltage spikes and finally applied to an operational amplifier configured as a comparator. All data referred to the OC protection are listed on page 9 of this datasheet.

4. Gate Drivers

Devices used to perform this task are the well-known IR2213, capable of 2A sink and 2A source maximum gate driving current, in a SO16W package; on page 2 is shown also the block schematic of the gate driving section of the module.

The IGBTs used in the PI-IPM (genV NPT 1200V - 25A from IR) do not need any negative gate drive voltage for their complete turn off, this simplifies the flyback power supply design avoiding the need of center tapped transformer outputs or the use of zener diodes to create the central common reference for the gate drivers floating ground. Though the IR2213 do have +/-2A of gate current capability, in the PI-IPM25P12B008 we use different gate resistor values for turn on and turn off as follows:

\[
\begin{align*}
\text{turn – on} & = 68\, \text{ohm} \\
\text{turn – off} & = 22\, \text{ohm}
\end{align*}
\]

Commonly realized through a diode-resistor series in parallel with a single resistor used in turn on only. Observed rise and fall times are around 250ns – 300ns depending on the output current level, this values are considered as pretty adequate for a 12.5A application at 16kHz symmetric PWM carrier, space vector modulation.

These gate drivers do provide levels shifting without any galvanic isolation, that is no opto-couplers are built inside. This turns out to be a major benefit in this stage where the usual 1μs delay of optos impacts on the system control as a systematic and fastidious delay.

5. DC bus and Input voltage feedback

The purpose of this block is to continuously check the voltage of the two supply lines of the system: Vin and DC bus. Vin is the only external power supply needed for all electronics in the EDB. The internal flyback regulator has its own under-voltage lockout to prevent all electronics from start working when an insufficient supply voltage is present; minimum recommended supply voltage is 12V. Low side gate drivers are directly fed from the Vin line and there is no further control to this voltage than their own under-voltage lockout. This is typically set at 8.5V and this level could be not sufficient to properly drive the IGBT gates, then it is advisable to check with the DSP the input voltage and impose that the system could start switching only when the Vin voltage is between 10V and 18V thus providing also an over-voltage control.

The DC bus voltage is also important for the system functioning and needs to be continuously kept under control. A resistor divider provides a partition coefficient of 2.44mV/V and a maximum mapped voltage of around 1100V

As the block schematic shows, it has to be taken into account that, to avoid false detections due to voltage spikes inevitably present on the partitioned voltage, a 1kHz passive filter has been inserted between the divider and the voltage follower buffer whose output is connected to one of the ADC inputs.
Fig. 1 – Maximum DC collector current vs. case temperature

Fig. 2 – Power Dissipation vs. Case Temperature

Fig. 3 – Forward SOA
$T_C = 25^\circ C; T_j \leq 150^\circ C$

Fig. 4 – Reverse Bias SOA
$T_j = 150^\circ C, V_{GE} = 15V$
Fig. 5 – Typical IGBT Output Characteristics
Tj = -40°C; tp = 300µs

Fig. 7 – Typical IGBT Output Characteristics
Tj = 125°C; tp = 300µs

Fig. 6 – Typical IGBT Output Characteristics
Tj = 25°C; tp = 300µs

Fig. 8 – Typical Diode Forward Characteristics
tp = 300µs
Fig. 9 – Typical $V_{CE}$ vs. $V_{GE}$

$T_j = -40^\circ C$

Fig. 10 – Typical $V_{CE}$ vs. $V_{GE}$

$T_j = 25^\circ C$

Fig. 11 – Typical $V_{CE}$ vs. $V_{GE}$

$T_j = 125^\circ C$

Fig. 12 – Typical Transfer Characteristics

$V_{CE} = 20V$; $t_p = 20\mu s$
Fig. 13 – Typical Energy Loss vs. $I_C$
$T_j = 125^\circ C; L = 200\mu H; V_{CE} = 600V;$
$R_g = 10\Omega; V_{GE} = 15V$

Fig. 15 – Typical Energy Loss vs. $R_g$
$T_j = 125^\circ C; L = 200\mu H; V_{CE} = 600V;$
$I_{CE} = 25A; V_{GE} = 15V$

Fig. 14 – Typical Switching Time vs. $I_C$
$T_j = 125^\circ C; L = 200\mu H; V_{CE} = 600V;$
$R_g = 10\Omega; V_{GE} = 15V$

Fig. 16 – Typical Switching Time vs. $R_g$
$T_j = 125^\circ C; L = 200\mu H; V_{CE} = 600V;$
$I_{CE} = 25A; V_{GE} = 15V$
Fig. 17 – Typical Diode $I_{RR}$ vs. $I_F$
$T_j = 125^\circ$C

Fig. 18 – Typical Diode $I_{RR}$ vs. $R_g$
$I_F = 25A; T_j = 125^\circ$C

Fig. 19 – Typical Diode $I_{RR}$ vs. $dI_F/dt$
$V_{DC} = 600V; V_{GE} = 15V; I_F = 25A; T_j = 125^\circ$C

Fig. 20 – Typical Diode $Q_{RR}$
$V_{DC} = 600V; V_{GE} = 15V; T_j = 125^\circ$C
Fig. 21 – Typical Diode $E_{REC}$ vs. $I_F$
$T_j = 125^\circ\text{C}$

Fig. 22 – Typical Capacitance vs. $V_{CE}$
$V_{GE} = 0\text{V}$; $f = 1\text{MHz}$

Fig. 23 – Typical Gate Charge vs. $V_{GE}$
$I_C = 25\text{A}$; $L = 600\mu\text{H}$; $V_{CC} = 600\text{V}$
Fig. 24 – Normalized Transient Impedance, Junction-to-copper plate

Notes:
1. Duty factor \( D = \frac{t_1}{t_2} \)
2. Peak \( T_s = P_{D_M} \times Z_{V_J} + T_c \)

\( t_1 \), Rectangular Pulse Duration (sec)
**Fig. CT.1 - Gate Charge Circuit (turn-off)**

**Fig. CT.2 - RBSOA Circuit**

**Fig. CT.3 - S.C. SOA Circuit**

**Fig. CT.4 - Switching Loss Circuit**

**Fig. CT.5 - Resistive Load Circuit**
**Fig. CT.1 - Gate Charge Circuit (turn-off)**

**Fig. CT.2 - RBSOA Circuit**

**Fig. CT.3 - S.C. SOA Circuit**

**Fig. CT.4 - Switching Loss Circuit**

**Fig. CT.5 - Resistive Load Circuit**
**Fig. WF.1 - Typ. Turn-off Loss Waveform**
@ $T_j=125^\circ C$ using Fig. CT.4

**Fig. WF.2 - Typ. Turn-on Loss Waveform**
@ $T_j=125^\circ C$ using Fig. CT.4

**Fig. WF.3 - Typ. Diode Recovery Waveform**
@ $T_j=125^\circ C$ using Fig. CT.4

**Fig. WF.4 - Typ. S.C. Waveform**
@ $T_C=150^\circ C$ using Fig. CT.3
Fig. PD1 – Total Dissipated Power vs. $f_{SW}$
$I_{outRMS} = 3.5A$, $V_{DC} = 530V$, $T_C = 55^\circ C$

Fig. PD2 – Total Dissipated Power vs. $f_{SW}$
$I_{outRMS} = 5A$, $V_{DC} = 530V$, $T_C = 55^\circ C$

Fig. PD3 – Total Dissipated Power vs. $f_{SW}$
$I_{outRMS} = 10A$, $V_{DC} = 530V$, $T_C = 40^\circ C$

Fig. TF1 – Thermal Sensor Voltage Feedback vs. Base-plate Temperature
PIIPM family part number identification

PIIPM 25 P 12 B 008 X

1- Device type (Programmable Isolated Intelligent Power Module)

2- Power package code
   2.1- Current rating Code [A]
   2.2- Sensing Resistors configuration
        P = on 3 phases
        Q = on 2 phases (*)
        R = on 1 phase (only for Matrix config) (*)
        E = on 3 emitters
        F = on 2 emitters (*)
        G = on 1 emitter (*)

   2.3- Voltage rating Code [V/100]
        06 = 600V
        12 = 1200V

   2.4- Power Module configuration code
        A = Bridge brake (*)
        B = Inverter
        C = Inverter + brake
        D = BBi (Bridge Brake Inverter)
        M = Matrix (*)

3- EDB configuration code
   See detailed Block Diagram

4- Status code
   • X = Sample (product with pre-qualification approval)
     • blank = Fully qualified product

note: * = contact factory for availability
Top board suggested footprint
(top view)

RS422 and JTAG Connectors mapping

These connectors do not have any orientation tag; please check their Pin 1 position on Power Module Frame Pins Mapping before inserting mate part.

JTAG and RS422 on-board connectors
Top view

Molex 53916-0204
mates with 54167-0208 or 52991-0208
PIIPM25P12B008 case outline and dimensions

Data and specifications subject to change without notice.
This product has been designed and qualified for Industrial Level.
Qualification Standards can be found on IR's Web Site.