Thermal design of capacitors for power electronics

1 Criteria for use
In order to scale a capacitor correctly for a particular application, the permissible ambient temperature has to be determined. This can be taken from the diagram “Permissible ambient temperature $T_A$ vs total power dissipation $P$” after calculating the power dissipation (see individual data sheets). For data sheets not contained in this data book, contact the nearest office of EPCOS.

Besides calculation of power dissipation $P$, the following examples illustrate determination of the thermal load for continuous and intermittent operation.

2 Calculation of power dissipation $P$
The total power dissipation $P$ is composed of the dielectric losses ($P_D$) and the resistive losses ($P_R$):

$$P = P_D + P_R$$  \hspace{1cm} (13)

$$P_D = \hat{u}_{ac}^2 \cdot \pi \cdot f_0 \cdot C \cdot \tan \delta_0$$  \hspace{1cm} (14)

$\hat{u}_{ac}$ peak value of symmetrical AC voltage applied to capacitor (see also section 2.2.3) V

$f_0$ fundamental frequency Hz

$C$ capacitance F

$\tan \delta_0$ dissipation factor of dielectric

$$P_R = I^2 \cdot R_S$$  \hspace{1cm} (15)

$I$ rms value of capacitor current A

$R_S$ series resistance at maximum hot-spot temperature $\Omega$

The $R_S$ figure at maximum hot-spot temperature is used to calculate the resistive losses. In selection charts and data sheets the figure is stated for 20 °C capacitor temperature. The conversion factors are as follows:

<table>
<thead>
<tr>
<th>MP capacitors</th>
<th>$R_{S70} = 1.20 \cdot R_{S20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MKV capacitors</td>
<td>$R_{S65} = 1.25 \cdot R_{S20}$</td>
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</table>
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2.1 Calculation example for continuous operation

For data on B2S855-C7255-K004, see individual data sheet, page 244.

- Electrical operating parameters
  - \( C_R = 2.5 \, \mu\text{F} \)
  - \( U_R = \text{DC 3000 V} \)
  - \( U_{ac} = 1500 \, \text{V} \)
  - \( f_0 = 300 \, \text{Hz} \)
  - \( I = 50 \, \text{A} \)
  - \( R_S(20 \, ^\circ\text{C}) = 1.4 \, \text{m}\Omega \)
  - \( R_S(85 \, ^\circ\text{C}) = 1.7 \, \text{m}\Omega \)
  - \( \tan \delta_0 = 2 \cdot 10^{-4} \)

2.1.1 Dielectric power dissipation \( P_D \)

This can be read from the upper diagram in the thermal data sheet as a function of the frequency. The diagram only applies to operation at the specified voltage \( U_{ac} \) (peak value of the symmetrical alternating voltage applied to the capacitor)

- for DC capacitors: \( U_{ac} = 0.1 \cdot U_R \)
- for AC capacitors: \( U_{ac} = U_R \)
- for GTO snubber capacitors: \( U_{ac} = U_R (\text{DC}) / 2 \)

\( P_D \) can be calculated for all other voltages by applying equation (14):

\[
P_D = \frac{U_{ac}^2}{2 \cdot \pi \cdot f_0 \cdot C \cdot \tan \delta_0}
\]

for \( f_0 = 300 \, \text{Hz} \), we read: \( P_D = 1.1 \, \text{W} \)
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2.1.2 Ohmic power dissipation $P_R$

This can be read from the middle diagram as a function of the current, or can be calculated using equation (15): $P_R = I^2 \cdot R_S$

For $I = 50\, \text{A}$, we read: $P_R = 4.3\, \text{W}$

2.1.3 Permissible ambient temperature

This can be read from the lower diagram as a function of the total power dissipation. Total power dissipation (equation (13)): $P = P_D + P_R = 5.4\, \text{W}$

In the example, the following permissible ambient temperature is obtained:

- For natural convection cooling: $T_{A\text{max}} = 55\, \text{°C}$
- For forced convection cooling (2 m/s): $T_{A\text{max}} = 67\, \text{°C}$
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2.2 Permissible ambient temperature in intermittent operation

The effective mean power dissipation $\bar{P}$ has to be determined for intermittent operation. The maximum hot-spot temperature $T_{HS}$ is also the scaling limit in intermittent operation.

$$\bar{P} = \frac{1}{t} \int_0^t P(t) \, dt \quad (16)$$

$\bar{P}$ mean power dissipation W

$P(t)$ power dissipation vs time W
dt time element s
t time s

In intermittent operation the calculation is simplified by introduction of the duty factor $t_1 / (t_1 + t_2)$ to become

$$\bar{P} = \frac{t_1}{t_1 + t_2} \cdot P \quad (17)$$

$\bar{P}$ mean power dissipation W

$t_1$ on time s

$t_2$ off time s

$P$ total power dissipation W

$t_1 + t_2$ cycle duration s

$t_1 / (t_1 + t_2)$ duty factor

Calculation example

Given:

$t_1 = 1650 \text{ s} \quad \text{on time}$

$t_2 = 2000 \text{ s} \quad \text{off time}$

$P = 5.4 \text{ W} \quad \text{total power dissipation}$

With equation (17) this becomes:

$$\bar{P} = \frac{1650}{1650 + 2000} \cdot 5.4 = 2.44 \text{ W}$$
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Figure 5
Permissible ambient temperature $T_A$ versus total power dissipation $P$

Natural cooling
Forced cooling 2 m/s
Permissible capacitor temperature

Reading from the diagram

- $T_{A_{\text{max}}}$ = 72 °C permissible ambient temperature for natural cooling in intermittent operation
- $\Delta T_P$ = 13 K mean temperature difference in intermittent operation

2.2.1 Check of thermal scaling in intermittent operation

It is necessary to ensure that the temperature limit $\Theta_{HS}$ is not exceeded.

Calculation of thermal resistance $R_{th}$ and thermal time constant $\tau_{th}$:

\[
R_{th} = \frac{\Delta T_P}{P} \quad (18)
\]

\[
\Delta T_P \quad \text{mean temperature difference in intermittent operation} \quad \text{K}
\]

\[
P \quad \text{mean power dissipation} \quad \text{W}
\]

The relationship between $R_{th}$ and $\tau_{th}$ is given by equation (11).

\[
\tau_{th} = m \cdot c_{\text{thcap}} \cdot R_{th}
\]

Calculation example

Given:

- $\Delta T_P$ = 13 K (from diagram, figure 5)
- $P$ = 2.44 W (calculated with equation (17), see page 48)
- $c_{\text{thcap}}$ = 1.3 Ws/Kg (specific thermal capacitance for selected capacitor)
- $m$ = 900 g (from data sheet)
Equation (18) produces
\[ R_{th} = \frac{\Delta T_p}{P} = \frac{13}{2.44} \]

And equation (11) produces
\[ \tau_{th} = m \cdot c_{th,\text{cap}} \cdot R_{th} = 900 \cdot 1.3 \cdot \frac{W_s}{K \cdot g} \cdot 5.3 \frac{K}{W} = 6200 \]

The generally valid correction factor \( \beta \) (figure 6) can be used for final calculation of the permissible ambient temperature in intermittent operation \( T_{A,\text{max}} \), allowing for the particular application.

\[ T_{A,\text{max}} \leq T_{HS} (1 - \beta) + \beta T_{AP} \quad (19) \]

- \( T_{A,\text{max}} \): permissible ambient temperature in intermittent operation °C
- \( T_{HS} \): max. hot-spot temperature °C
- \( \beta \): correction factor
- \( T_{AP} \): mean ambient temperature in intermittent operation °C

**Figure 6**
Correction factor \( \beta \) vs duty factor \( t_1/(t_1 + t_2) \)
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Calculation example
The on and off times stated on page 48 and the thermal time constant $\tau_{th}$ calculated on page 50 produce:

\[
\frac{t_1}{t_1 + t_2} = \frac{1650}{1650 + 2000} = 0.45 \quad \text{(duty factor)}
\]

\[
\frac{t_1 + t_2}{\tau_{th}} = \frac{(1650 + 2000)}{6200} = 0.6 \quad \text{(parameter in figure 6)}
\]

The correction factor $\beta = 1.15$ can be read from figure 6.
Equation (19) produces:

\[
T_{Amax} \leq 85 \left(1 - 1.15\right) + 1.15 \cdot 72
\]

\[
T_{Amax} = 70 \, ^\circ C \quad \text{(for natural cooling)}
\]

3 Load duration $t_{LDT}$ as a function of temperature $T$

The load duration of capacitors with organic dielectrics depends among other things on the hot-spot temperature produced in operation. By derivation from the Arrhenius equation (this describes temperature-dependent aging processes) a relation can be produced for the load duration on the basis of the maximum hot-spot temperature in a not too considerable temperature interval ($T_{hs} = T_{HS} ... T_{HS} - 7 \, ^\circ C$).

\[
t_{LDT_{hs}} = t_{LDT_{HS}} \cdot 2 \left(\frac{T_{HS} - T_{hs}}{c} \right)
\]  

\[
t_{LDT_{hs}} = \text{load duration at hot-spot temperature at operating point } h
\]

\[
t_{LDT_{HS}} = \text{load duration at maximum hot-spot temperature } h
\]

\[
T_{HS} = \text{maximum hot-spot temperature } ^\circ C
\]

\[
T_{hs} = \text{hot-spot temperature at operating point } ^\circ C
\]

\[
c = \text{Arrhenius coefficient } 7 \, ^\circ C
\]

4 Load duration $t_{LDU}$ as a function of voltage $U$

This produces, in analogous fashion to the temperature-dependent load-duration forecast, results that are only useful within relatively narrow limits ($U = 0.9 ... 1.1 \cdot U_R$). The voltage-dependent load duration of the capacitors can be approximated by a law of exponents:

\[
t_{LDU} = t_{LDU_h} \left(\frac{U_R}{U}\right)^n
\]

\[
t_{LDU} = \text{load duration at operating voltage } h
\]

\[
t_{LDU_h} = \text{load duration at rated voltage } h
\]

\[
U_R = \text{rated voltage } V
\]

\[
U = \text{operating voltage } V
\]

\[
n = \text{exponent which depends on the technology used}
\]