Thermal design of capacitors for power electronics

1 Criteria for use

In order to scale a capacitor correctly for a particular application, the permisible 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):

Generally a secondary sinusoidal AC voltage can be used for calculating with sufficient accuracy.

$$P = P_D + P_R \tag{13}$$

$$P_D = \hat{u}_{ac}^2 \cdot \pi \cdot f_0 \cdot C \cdot \tan \delta_0 \tag{14}$$

$\hat{u}_{ac}$	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	

$$P_R = I^2 \cdot R_S \tag{15}$$

I	rms value of capacitor current	A
R_S	series resistance at maximum hot-spot temperature	Ω

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:

MP capacitors	$R_{S70} = 1.20 \cdot R_{S20}$
MKV capacitors	$R_{S85} = 1.25 \cdot R_{S20}$
MKK capacitors	$R_{S70} = 1.20 \cdot R_{S20}$
MPK capacitors	$R_{S85} = 1.25 \cdot R_{S20}$

2.1 Calculation example for continuous operation

For data on B25855-C7255-K004, see individual data sheet, page 244.

- *Electrical operating parameters*

C_R	= 2.5 µF
U_R	= DC 3000 V
$\hat{u}_{ac}$	= 1500 V
f_0	= 300 Hz
I	= 50 A
R_S(20 °C)	= 1.4 mΩ
R_S(85 °C)	= 1.7 mΩ
$\tan \delta_0$	$= 2 \cdot 10^{-4}$

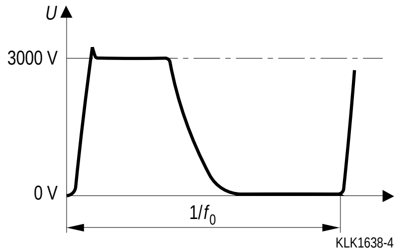


Figure 1

Voltage connected to capacitor versus time

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 $\hat{u}_{ac}$ (peak value of the symmetrical alternating voltage applied to the capacitor)

- for DC capacitors: $\hat{u}_{ac} = 0.1 \cdot U_R$
- for AC capacitors: $\hat{u}_{ac} = U_R$
- for GTO snubbber capacitors: $\hat{u}_{ac} = U_R$ (DC) / 2

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

$$P_D = \hat{u}_{ac}^2 \cdot \pi \cdot f_0 \cdot C \cdot \tan \delta_0$$

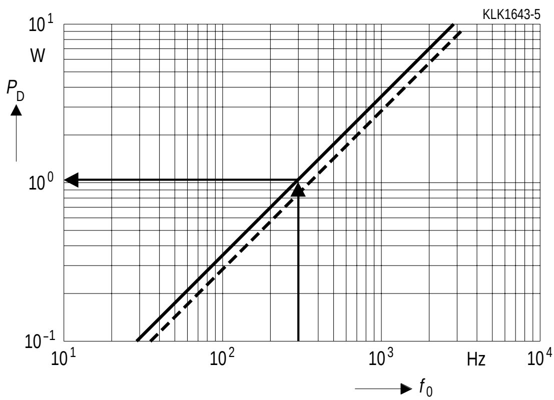


Figure 2

Dielectric power dissipation P_D versus repetition frequency f_0

$\hat{u}_{ac}$ = 1500 V ————

$\hat{u}_{ac}$ = 1350 V - - - - - -

for f_0 = 300 Hz, we read: P_D = 1.1 W

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): $P_R = I^2 \cdot R_S$

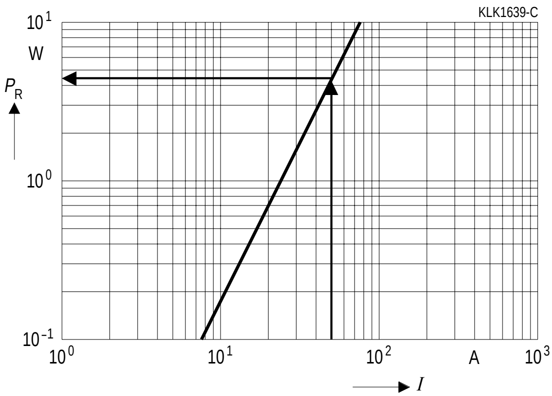


Figure 3

Ohmic power dissipation P_R versus rms current value I

R_S (85 °C) = 1.7 mΩ

for I = 50 A, we read: P_R = 4.3 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)): $P = P_D + P_R = 5.4$ W

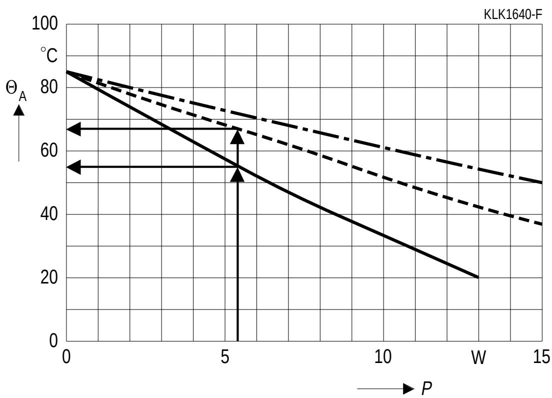


Figure 4

Permissible ambient temperature T_A versus total power dissipation P

Natural cooling
Forced cooling 2 m/s
Permissible capacitor temperature

Upright mounting position

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

For natural convection cooling: T_{Amax} = 55 °C
For forced convection cooling (2 m/s): T_{Amax} = 67 °C

2.2 Permissible ambient temperature in intermittent operation

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

$$\overline{P} = \frac{1}{t}\int_0^t P(t)dt \qquad (16)$$

$\overline{P}$	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

$$\overline{P} = \frac{t_1}{t_1 + t_2} \cdot P \qquad (17)$$

$\overline{P}$	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:

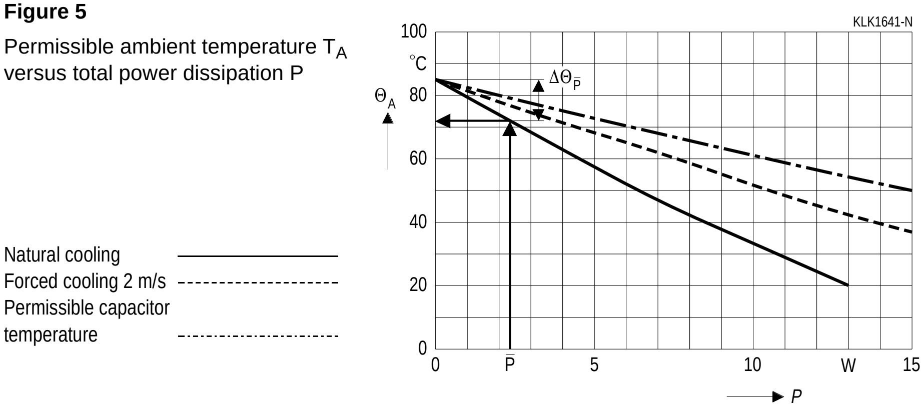
t_1 = 1650 s (on time)
t_2 = 2000 s (off time)
P = 5.4 W (total power dissipation)

With equation (17) this becomes:

$$\overline{P} = \frac{1650}{(1650 + 2000)} \cdot 5.4 = 2.44\ \text{W}$$

Figure 5

Permissible ambient temperature T_A versus total power dissipation P



Reading from the diagram

T_{Amax}	= 72 °C	permissible ambient temperature for natural cooling in intermittent operation
$\Delta T_{\bar{P}}$	= 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 Θ_{HS} is not exceeded.

Calculation of thermal resistance R_{th} and thermal time constant τ_{th}:

$$R_{th} = \frac{\Delta T_{\bar{P}}}{\bar{P}} \quad (18)$$

$\Delta T_{\bar{P}}$	mean temperature difference in intermittent operation	K
$\bar{P}$	mean power dissipation	W

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

$\tau_{th} = m \cdot c_{thcap} \cdot R_{th}$

Calculation example

Given:

$\Delta T_{\bar{P}}$	=	13 K	(from diagram, figure 5)
$\bar{P}$	=	2.44 W	(calculated with equation (17), see page 48)
c_{thcap}	≈	$1.3 \frac{Ws}{K \cdot g}$	(specific thermal capacitance for selected capacitor)
m	=	900 g	(from data sheet)

Equation (18) produces

$$R_{th} = \frac{\Delta T_{\overline{P}}}{\overline{P}} = \frac{13}{2{,}44}$$

And equation (11) produces

$$\tau_{th} = m \cdot c_{thcap} \cdot R_{th} = 900 \cdot 1.3\ \frac{Ws}{K \cdot g} \cdot 5.3\ \frac{K}{W} = 6200$$

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

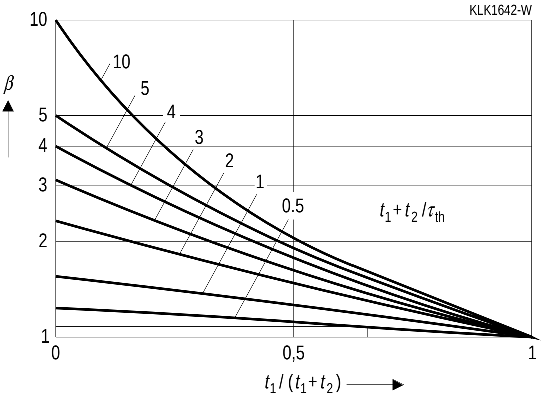


Figure 6

Correction factor β vs duty factor $t_1/(t_1 + t_2)$

$$T_{Amax} \leq T_{HS}\,(1 - \beta) + \beta T_{AP} \qquad (19)$$

T_{Amax}	permissible ambient temperature in intermittent operation	°C
T_{HS}	max. hot-spot temperature	°C
β	correction factor	
$T_{A\overline{P}}$	mean ambient temperature in intermittent operation	°C

Calculation example

The on and off times stated on page 48 and the thermal time constant τ_{th} calculated on page 50 produce:

$$\frac{t_1}{(t_1 + t_2)} = \frac{1650}{(1650 + 2000)} = 0.45 \qquad \text{(duty factor)}$$

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

The correction factor $\beta \approx 1.15$ can be read from figure 6.

Equation (19) produces:

$T_{Amax} \leq 85\,(1 - 1.15) + 1.15 \cdot 72$

T_{Amax} = **70 °C** (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 ($T_{hs} = T_{HS} \ldots T_{HS} - 7$ K).

$$t_{LDT_{hs}} = t_{LDT_{HS}} \cdot 2^{\left(\frac{T_{HS} - T_{hs}}{c}\right)} \qquad (20)$$

$t_{LDT_{hs}}$	load duration at hot-spot temperature at operating point	h
$t_{LDT_{HS}}$	load duration at maximum hot-spot temperature	h
T_{HS}	maximum hot-spot temperature	°C
T_{hs}	hot-spot temperature at operating point	°C
c	Arrhenius coefficient	7 °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 ($U = 0.9 \ldots 1.1 \cdot U_R$). The voltage-dependent load duration of the capacitors can be approximated by a law of exponents:

$$t_{LD_U} = t_{LD_{U_R}} \left(\frac{U_R}{U}\right)^n \qquad (21)$$

t_{LD_U}	load duration at operating voltage	h
$t_{LD_{U_R}}$	load duration at rated voltage	h
U_R	rated voltage	V
U	operating voltage	V
n	exponent which depends on the technology used	