Harjoitus 6   Solutions

Tehtävä 1

Average losses for the whole 20ms durations

$$\overline{P}_{\mathrm{H}} = \frac{25 \cdot 300\,\mathrm{W} \cdot 300\,\mu s}{20\,\mathrm{ms}} = 112{,}5\,\mathrm{W}$$

Look at the figure below. As per "accelerated super position principle" this is inserted to end on the half way of the pulse package. Duration of pulses is 10 ms so there is a 5 ms gap from the average power to start of the pulses.

Book recommends to only calculated few (2) of the last pulses accurately and calculate start of the pulse series with one equivalent pulse. There is 25 pulses in the series so equivalent pulse is the average power of the remaining 23 pulses as so:

$$\overline{P}_{\mathrm{H}}^{'} = \frac{23 \cdot 300\,\mathrm{W} \cdot 300\,\mu s}{22 \cdot 400\,\mu s + 300\,\mu s} \approx 227{,}5\,\mathrm{W}$$

This figure shows the process more clearly
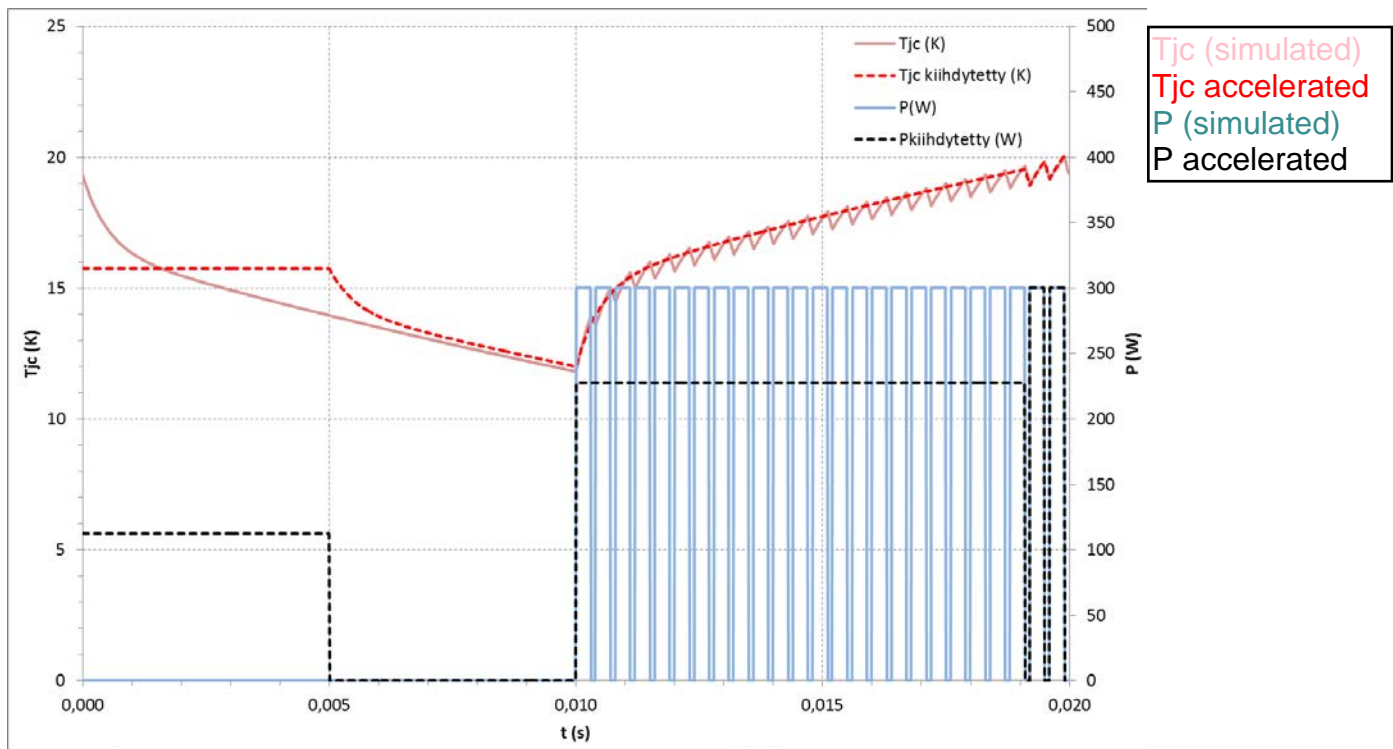
Manufacturer has given time transient thermal resistance in both graphical and as a series expansion, Thermal impedance Z_jc(t) as a function of pulse duration (t)

$$Z_{\mathrm{th\,jc}}(t) = 0{,}126\,{K}\!/\!{\mathrm{W}}\left(1 - e^{-\frac{t}{30\,\mathrm{ms}}}\right) + 0{,}014\,{K}\!/\!{\mathrm{W}}\left(1 - e^{-\frac{t}{0{,}5\,\mathrm{ms}}}\right)$$

Temperature at the end of last pulse can be calculated using previous page time scale

$$T_{jc}(19,9\,\text{ms}) = \overline{P}_H\left[Z_{th\,jc}(\infty) - Z_{th\,jc}(19,9\,\text{ms} - 5\,\text{ms})\right]$$
$$+ \overline{P}'_H\left[Z_{th\,jc}(19,9\,\text{ms} - 10\,\text{ms}) - Z_{th\,jc}(19,9\,\text{ms} - 19,1\,\text{ms})\right]$$
$$+ \hat{P}_H\left[Z_{th\,jc}(19,9\,\text{ms} - 19,2\,\text{ms}) - Z_{th\,jc}(19,9\,\text{ms} - 19,5\,\text{ms})\right]$$
$$+ \hat{P}_H Z_{th\,jc}(19,9\,\text{ms} - 19,6\,\text{ms})$$

Result of this may differ depending if graphical values are used or not. Graphical values seem to be on the upper end of the scale, tho, this might be on purpose to avoid underengineering

t	$Z_{th\,jc}(t)$ kaavasta	$Z_{th\,jc}(t)$ käyrästä
∞ ms	0,14 K/W	0,15 K/W
14,9 ms	0,0633 K/W	0,065 K/W
9,9 ms	0,0494 K/W	0,053 K/W
0,8 ms	0,0145 K/W	0,015 K/W
0,7 ms	0,0135 K/W	0,014 K/W
0,4 ms	0,0094 K/W	0,010 K/W
0,3 ms	0,0076 K/W	0,008 K/W

Z(t) Numerical, Z(t) graphical

Using graphical values

$$T_{jc}(19,9\,\text{ms}) = 112,5\,\text{W}\left[0,15\,\text{K/W} - 0,065\,\text{K/W}\right]$$
$$+ 227,5\,\text{W}\left[0,053\,\text{K/W} - 0,015\,\text{K/W}\right]$$
$$+ 300\,\text{W}\left[0,014\,\text{K/W} - 0,010\,\text{K/W}\right]$$
$$+ 300\,\text{W} \cdot 0,008\,\text{K/W}$$
$$= 21,8\,\text{K}$$

Using equation

$$T_{jc}(19,9\,\text{ms}) = 112,5\,\text{W}\left[0,14\,\text{K/W} - 0,0633\,\text{K/W}\right]$$
$$+ 227,5\,\text{W}\left[0,0494\,\text{K/W} - 0,0145\,\text{K/W}\right]$$
$$+ 300\,\text{W}\left[0,0135\,\text{K/W} - 0,0094\,\text{K/W}\right]$$
$$+ 300\,\text{W} \cdot 0,0076\,\text{K/W}$$
$$= 20,1\,\text{K}$$

Values on the graph are based on numerical values and book equations 8.14 and 8.15. You may do this yourself with excel.
As shown, accelerated super position principle gives very accurate results... well at least in this example
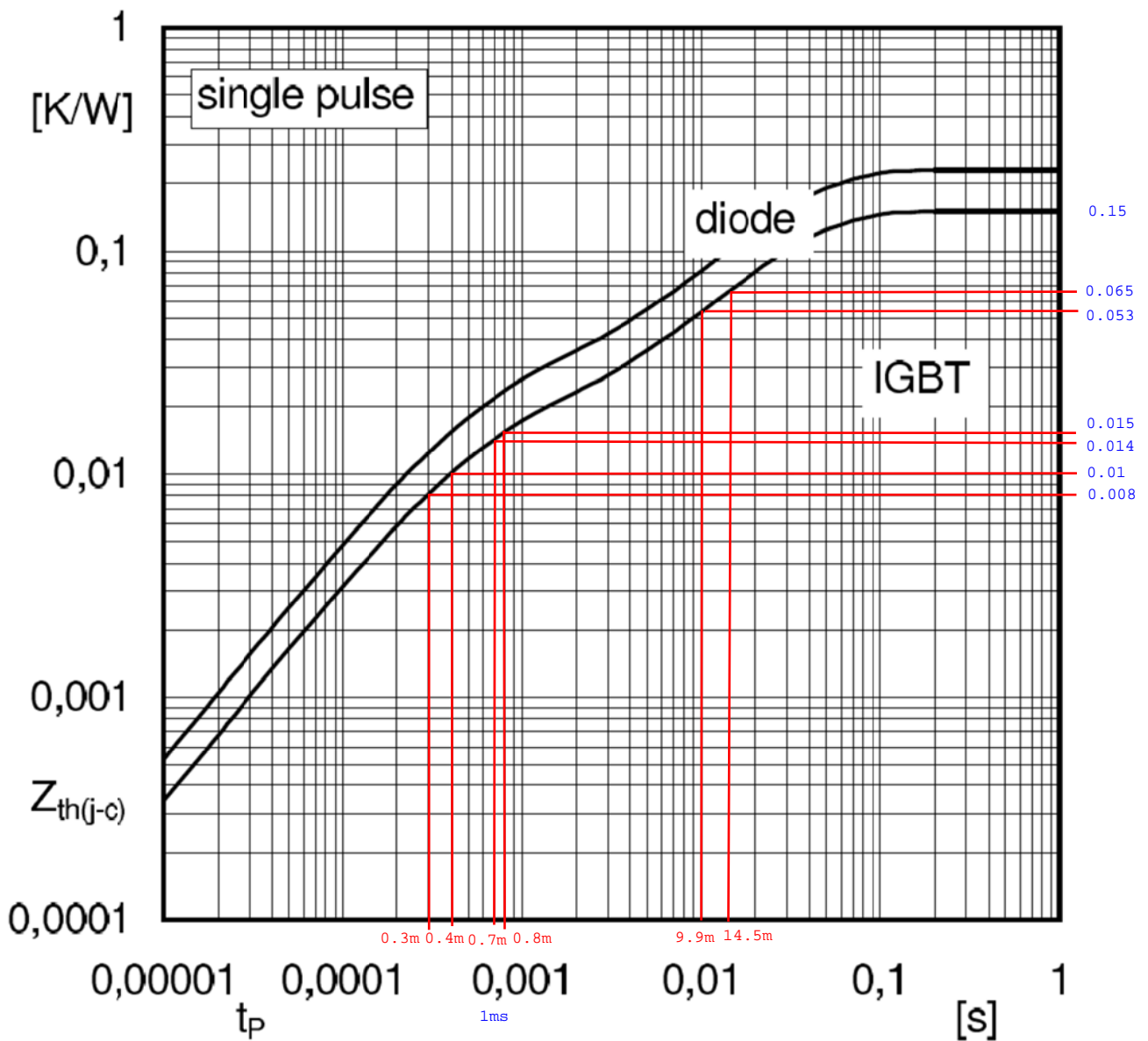
| Rth(j-c) | per IGBT | | 0.14 | K/W |

$$Z_{th}(t) = R_1\left(1 - \exp\left(-\frac{t}{\tau_1}\right)\right) + R_2\left(1 - \exp\left(-\frac{t}{\tau_2}\right)\right) \qquad (4\text{-}2)$$

For SEMiX modules, the coefficients R_1, τ_1, and R_2, τ_2 can be determined using the data sheet values as given in Tab. 1-1.

		IGBT, CAL diode	Thyristor, rectifier diode
R_1	[K/W]	0.9 x $R_{th(j-c)}$	0.85 x $R_{th(j-c)}$
R_2	[K/W]	0.1 x $R_{th(j-c)}$	0.15 x $R_{th(j-c)}$
τ_1	[sec]	0.03	0.055
τ_2	[sec]	0.0005	0.0035
Tab. 1-1 Parameters for $Z_{th(j-c)}$ calculation using equation (4-2)			

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Exercise 2

Required R_{thCA} is < 0.26 K/W

a) Datasheet notes that page 243 top right, figure suggests element KK32 (Ø18 mm)

b) Again we might notice that required airflow is > 30 l/s

c) Same page bottom figure gives pressure difference of $\Delta p = 25$ N/m^2

d) Volume calculation: KK32 outside measures are (slotted part)

$2 \times 22 \times 140 \times 120$ mm^3 (some measures were taken from image)
$\Rightarrow V = 0.74$ dm^3

Equation (8.18): $V = 1.96 \times R_{th}^{-1.67} \times P^{-0.251}$ can be solved for R_{th}

$$R_{th} = \left(\frac{V}{1.96 \times P^{-0.251}}\right)^{\frac{1}{-1.67}} = \left(\frac{0.74}{1.96 \times 205^{-0.251}}\right)^{\frac{1}{-1.67}} \approx \boldsymbol{0.81\ K/W}$$

Using equation (8.16), we must calculate the element **cooling surface area**. Measuring carefully from the picture.

6 fins at the front:
$$2 \times (2 \times 17\ mm + 2 \times 15.5\ mm + 2 \times 14.5\ mm) \times 120\ mm = 2.26\ dm^2$$

3 bottom fins: $\qquad\qquad\qquad\qquad 2 \times 3 \times 8.4\ mm \times 120\ mm = 0.6\ dm^2$

4 Branches in the element:
$$\Rightarrow \quad \text{Total fin area: } 4 \times (2.26 + 0.6) = 11.4\ dm^2$$

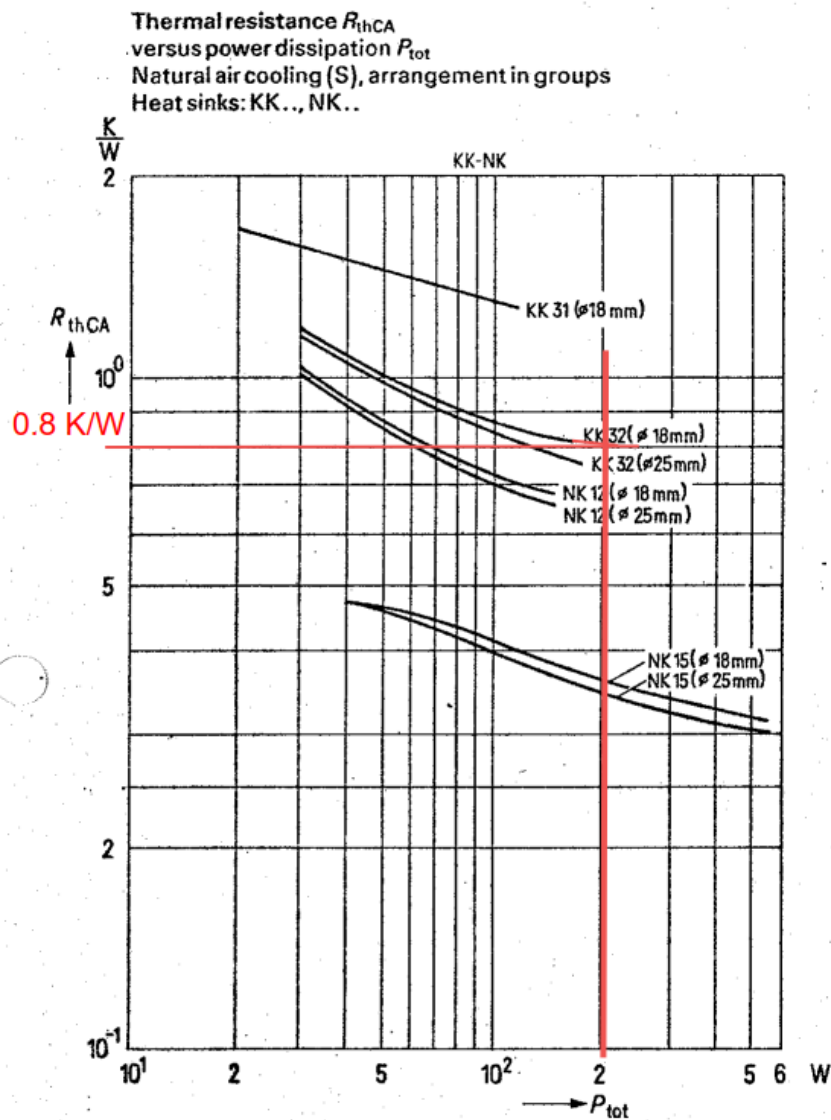Rest of the element = Casebody area – thyristor surface area

$4 \times [(70\ mm - 9 \times 2.5\ mm) + (70\ mm - 6 \times 2.5\ mm)] \times 120\ mm - 2\pi \times (20mm)^2 = 4.7\ dm^2$

$\Rightarrow A = 11.4 + 4.7 = 16.1\ dm^2$

$$R_{th} = 11.7 \times A^{-0.7} \times p^{-0.15} = 11.7 \times 16.1^{-0.7} \times 205^{-0.15} \approx \boldsymbol{0.75\ K/W}$$

Page 243 top left graph gives natural cooling thermal resistance $R_{th} = \boldsymbol{0.72 \dots 0.80}$, Extrapolating to 205 W power, when contact surface is Ø25 .. 18 mm.

Thermal resistance R_{thCA}
versus power dissipation P_{tot}
Natural air cooling (S), arrangement in groups
Heat sinks: KK.., NK..

We may conclude that both volume and surface-area based calculations are somewhat reasonably good estimates. Clearly <10 % error is achieved. Using volumetric estimation required calculations are even simpler.

e) Calculate required airflow using figure 8.11.
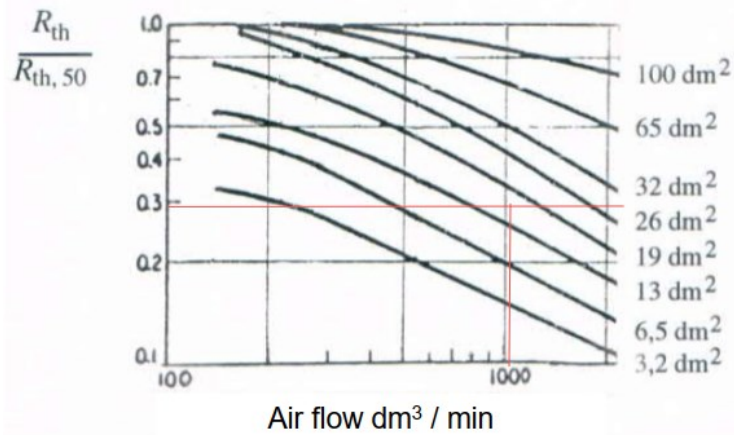Calculate base value $R_{th}(50)$:
$$R_{th}(50) = 9.09 \times A^{-0.824} = 9.09 \times 16.1^{-0.824} = 0.92 \; K/W$$

We wish to have R_{th} value below < 0.26 K/W,
Relative index $R_{th}/R_{th}(50) = 0.26/0.92 = 0.28$.

If surface area is not calculated, it can be estimated using volume using equation (8.16) and solving for Area A.

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$$\frac{R_{th}}{R_{th,\,50}}$$

Change in thermal resistance when the base value is Rth with natural air flow and 50 K temperature increase of the element. Parameter is the area of the cooling element.

Draw figure 8.11 at $R_{th}/R_{th}(50) = 0.28$ ratio
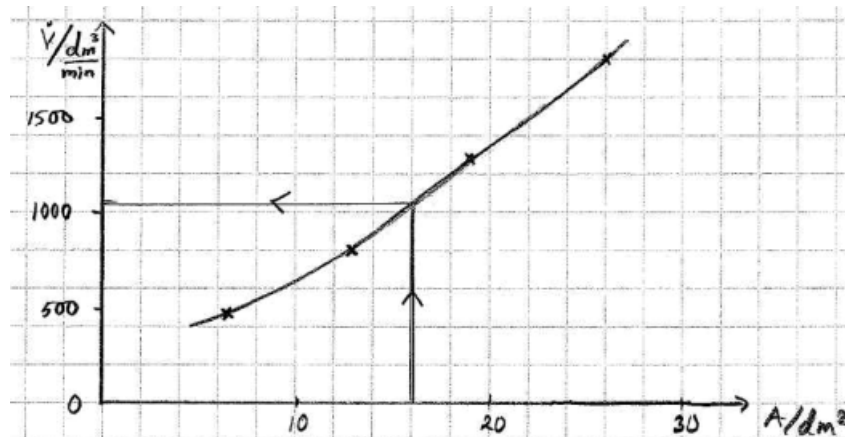
Reading airflow figure at 16.1 dm^2 :

$$=> dV/dt = 1050 \; dm^3/min = 17.5 \; l/s$$

Comparing to previous value of $30 \; l/s$, we may conclude that the error is massive, although we are in the correct ballpark. Page 243 top right figure notes that Ø25mm contact area required airflow is $17.4 \; l/s$, which is close to previous calculation.

Therefore, we note that contact area diameter is pretty substantial parameter when using forced cooling. Reason for this is the element internal thermal resistance which effect is magnified when the Element-Air surface resistance lowers

Previously conducted exercise was to research the functionality of the rule of thumb based formula and to get a feel of using it.

Naturally using datasheets is always better if available. If an element is built by oneself there will not be a datasheet.

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These rule of thumb equations are of great benefit in the beginning of the design process. Specially if the sink module has not been even built yet.

NOTE! With self-made elements, airgaps between fins cannot be made arbitrarily small, as air will not flow through small gaps. Take note from commercial elements with their hole sizes and measures