Resonance Tank Capacitor and Output Capacitor

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Inputs and claculated parameters

```
V_In_min 360.0 V_In_max 400.0 Vo_nom 48.0 Power   1200.0
V_In_nom 380.0   Vo_min  42.0 Vo_max 54.0 f_nom 100000.0
```

```
  Lnc    3.000    Lm_uH      65.392     Ioe_rms  7.636 Re_110     22.637
  Qec    0.550 fsw_min  60170.000     Ios_rms 30.545     Cr        0.0
Cr_nF  116.209 fsw_max 156220.000      Ir_rms 10.354     Lr   0.000022
    n    4.000  Im_rms       6.992 L_second_uH  4.087     Lm   0.000065
Lr_uH   21.797      Io      25.000      Re_nom 24.901
```

Output capacitor Co

Formulas

Basic sizing (capacitive ripple only) $C_o \geq C_{o_{min}}$

$$C_{o_{min}} = \frac{I_o}{8\, f_{sw}\, \Delta V_{outC}}$$

$$\Delta V_{outC} = \frac{I_o}{8\, f_{sw}\, C_o}$$

Where:

- C_o : Output capacitance (Farads, F)
- I_o : Output load current (Amperes, A)
- f_{sw} : Switching frequency of the converter (Hertz, Hz)
- ΔV_{out} : Maximum allowed output voltage ripple (Volts, V)
- ESR : Equivalent Series Resistance of the capacitor (Ω)

ESR-related terms $ESR_{max} = \dfrac{\Delta V_{outR}}{I_{rect\_peak}}$

$$\Delta V_{outR} = I_{rect\_peak} \cdot ESR$$

Where $I_{rect\_peak} = \dfrac{\pi}{2}\, I_o$

So:
$$\Delta V_{outR} = \frac{\pi}{2}\, I_o \cdot ESR$$

Capacitor RMS current $I_{C_o} = I_o \sqrt{\dfrac{\pi^2}{8} - 1}$

Total ripple — vector (RMS) sum with 90° phase shift $\Delta V_{out} = \sqrt{\Delta V_{outC}^2 + \Delta V_{outR}^2}$

$$\Delta V_{out} = \sqrt{\left(\frac{I_o}{8\, f_{sw}\, C_o}\right)^2 + (I_{rect\_peak} \cdot ESR)^2}$$

Replace I_{rect_peak}:
$$\Delta V_{out} = \sqrt{\left(\frac{I_o}{8\, f_{sw}\, C_o}\right)^2 + \left(\frac{\pi}{2}\, I_o \cdot ESR\right)^2}$$

Solve for C_o (RMS sum) $C_o \geq \dfrac{I_o}{8\, f_{sw} \sqrt{\Delta V_{out}^2 - \left(\frac{\pi}{2}\, I_o \cdot ESR\right)^2}}$

Condition: $\Delta V_{out} > \dfrac{\pi}{2}\, I_o \cdot ESR$

Solve for ESR (RMS sum) $ESR \leq \dfrac{1}{\frac{\pi}{2}\, I_o} \sqrt{\Delta V_{out}^2 - \left(\frac{I_o}{8\, f_{sw}\, C_o}\right)^2}$

Optional split of ripple budget (50%-50% rule) $\Delta V_{outR} < \dfrac{\Delta V_{out,max}}{2}$

$$\Delta V_{outC} < \frac{\Delta V_{out,max}}{2}$$

Implied bounds with 50/50 split:

$$C_o \geq \frac{I_o}{8\, f_{sw}\left(\frac{\Delta V_{out,max}}{2}\right)} = \frac{I_o}{4\, f_{sw}\, \Delta V_{out,max}}$$

$$ESR \leq \frac{\frac{\Delta V_{out,max}}{2}}{\frac{\pi}{2}\, I_o} = \frac{\Delta V_{out,max}}{\pi\, I_o}$$

Numerical Implementation of the Formulas 50% 50%

We must use fsw_min to the worst case

$$\mathrm{Io} = 25.000 \ \ (\mathrm{A})$$

$$\mathrm{fsw}_{min} = 60170.000 \ \ (\mathrm{Hz})$$

$$\mathrm{DV} = 0.250 \ \ (\mathrm{vpp})$$

$$\begin{aligned}\mathrm{Co}_{min_{uF}} &= 1 \times 10^6 \cdot \frac{\mathrm{Io}}{4 \cdot \mathrm{fsw}_{min} \cdot \mathrm{DV}} \\ &= 1 \times 10^6 \cdot \frac{25.000}{4 \cdot 60170.000 \cdot 0.250} \\ &= 415.489 \ \ (\mathrm{uF})\end{aligned}$$

$$\begin{aligned}\mathrm{ESR}_{max_m} &= 1 \times 10^3 \cdot \frac{\mathrm{DV}}{\mathrm{Io} \cdot \pi} \\ &= 1 \times 10^3 \cdot \frac{0.250}{25.000 \cdot 3.142} \\ &= 3.183 \ \ (\mathrm{m\Omega})\end{aligned}$$

$$\begin{aligned}I_{Co} &= \mathrm{Io} \cdot \sqrt{\frac{(\pi)^2}{8} - 1} \\ &= 25.000 \cdot \sqrt{\frac{(3.142)^2}{8} - 1} \\ &= 12.086 \ \ (\mathrm{Arms})\end{aligned}$$

First proposition

B40910A8127M000 aluminum electrolytic capacitors with Temp_max = 150°C, Below a screenshoot of the datasheet [2].

TDK

Hybrid polymer aluminum electrolytic capacitors B40910

Very high ripple current – up to 150 °C

Technical data and ordering codes

C_R 120 Hz 20 °C µF	Case dimensions[1] d x l mm	ESR_{max} 100 kHz 20 °C Ω	$I_{AC,R}$ 100 kHz 125 °C A	$I_{AC,max}$ 100 kHz 135 °C A	Ordering code (composition see below)
V_R = 63 V DC					
82	10 x 10.2 | 10 x 10.5	0.022	4.0	2.8	B40910A8826M***
100	10 x 10.2 | 10 x 10.5	0.022	4.0	2.8	B40910A8107M***
100	10 x 12.5 | 10 x 12.8	0.017	4.6	3.2	B40910B8107M***
120	10 x 12.5 | 10 x 12.8	0.017	4.6	3.2	B40910A8127M***
150	10 x 16.5 | 10 x 16.8	0.013	5.5	3.8	B40910A8157M***
180	10 x 16.5 | 10 x 16.8	0.013	5.5	3.8	B40910A8187M***

Figure 1: B40910A8127M000 aluminum electrolytic capacitors with Temp_max = 150°C

Let's start with a configuration of 6 capacitors in parallel, in the worst case ($C_{capa} = C_{min}$ of the datasheet)

$$\mathrm{Nb}_{capa} = 6$$

$$C_{capa_{nom}} = 120 \ \ (\mathrm{uF})$$

$$\mathrm{Margin} = 20 \ \ (\backslash\%)$$

$$C_{capa} = C_{capa_{nom}} \cdot \left(1 - \frac{\mathrm{Margin}}{100}\right) = 120 \cdot \left(1 - \frac{20}{100}\right) \qquad = 96.000 \ \ (\mathrm{uF, \ Worst \ case})$$

$$C_{eq} = C_{capa} \cdot \mathrm{Nb}_{capa} = 96.000 \cdot 6 \qquad = 576.000 \ \ (\mathrm{uF} > 415\mathrm{uF \ ok})$$

$$\mathrm{ESR}_{capa} = 17 \ \ (\Omega \ @ \ 100\mathrm{kHz})$$

$$\mathrm{ESR}_{eq} = \frac{\mathrm{ESR}_{capa}}{\mathrm{Nb}_{capa}} = \frac{17}{6} \qquad = 2.833 \ \ (\Omega < 3.18\mathrm{m \ OK})$$

$$\mathrm{Icapa}_{max} = 4.600$$

$$\begin{aligned} \mathrm{Ieq}_{max} &= \mathrm{Icapa}_{max} \cdot \mathrm{Nb}_{capa} \\ &= 4.600 \cdot 6 \\ &= 27.600 \ \ (@ \ \mathrm{Arms} \ @ \ 125^\circ\mathrm{C} \ 100\mathrm{kHz} > 12.08\mathrm{Arms \ ok}) \end{aligned}$$

I_rect_peak

$$I_{rect_{peak}} = \mathrm{Io} \cdot \frac{\pi}{2} = 25.000 \cdot \frac{3.142}{2} \qquad = 39.270 \ \ (\mathrm{A})$$

Voltage ripples

$$\begin{aligned}\Delta_{V_{out}} &= \sqrt{\left(\frac{\mathrm{Io}}{8 \cdot \mathrm{fsw}_{min} \cdot C_{eq} \cdot 1 \times 10^{-6}}\right)^2 + \left(\frac{\pi}{2} \cdot \mathrm{Io} \cdot \mathrm{ESR}_{eq} \cdot 1 \times 10^{-3}\right)^2} \\ &= \sqrt{\left(\frac{25.000}{8 \cdot 60170.000 \cdot 576.000 \cdot 1 \times 10^{-6}}\right)^2 + \left(\frac{3.142}{2} \cdot 25.000 \cdot 2.833 \cdot 1 \times 10^{-3}\right)^2} \\ &= 0.143 \ \ (\mathrm{V} < 0.25\mathrm{V\ Ok})\end{aligned}$$

Self heating

Power Dissipation of Each Capacitor

$$\begin{aligned}I_{each_{capa}} &= \frac{I_{Co}}{\mathrm{Nb}_{capa}} \\ &= \frac{12.086}{6} \\ &= 2.014 \ \ (\mathrm{A})\end{aligned}$$

$$\begin{aligned}P_{selfHeating} &= \mathrm{ESR}_{capa} \cdot 1 \times 10^{-3} \cdot \left(I_{each_{capa}}\right)^2 \\ &= 17 \cdot 1 \times 10^{-3} \cdot (2.014)^2 \\ &= 0.069 \ \ (\mathrm{W})\end{aligned}$$

Estimation of Thermal Resistance Rth

$$\Delta_T = 150 - 125 \qquad = 25 \ \ (^{\circ}\mathrm{C})$$

$$\mathrm{ESR} = 0.017$$

$$I = 4.600 \ \ (\mathrm{Arms})$$

$$\begin{aligned}P_{dissip} &= \mathrm{ESR} \cdot (I)^2 \\ &= 0.017 \cdot (4.600)^2 \\ &= 0.360 \ \ (\mathrm{W})\end{aligned}$$

$$\begin{aligned}R_{th} &= \frac{\Delta_T}{P_{dissip}} \\ &= \frac{25}{0.360} \\ &= 69.498 \ \ (^{\circ}\mathrm{C/W})\end{aligned}$$

The self heating estimation and the max ambiant temp

$$\begin{aligned}\Delta_T &= P_{selfHeating} \cdot R_{th} \\ &= 0.069 \cdot 69.498 \\ &= 4.794 \;\; (^\circ\mathrm{C} => \text{low delta temp})\end{aligned}$$

$$\begin{aligned}\text{Margin} &= 30 \;\; (^\circ\mathrm{C}) \\ T_{max} &= 150 \\ T_{amb_{max}} &= T_{max} - \Delta_T - \text{Margin} \\ &= 150 - 4.794 - 30 \\ &= 115.206 \;\; (^\circ\mathrm{C})\end{aligned}$$

Voltage margin

$$\begin{aligned}\mathrm{Vo}_{max} &= 54.000 \;\; (\mathrm{VDC}) \\ V_{max_{datasheet}} &= 63 \;\; (\mathrm{VDC}) \\ \text{Voltage}_{Margin} &= 100 \cdot \frac{V_{max_{datasheet}} - \mathrm{Vo}_{max}}{V_{max_{datasheet}}} \\ &= 100 \cdot \frac{63 - 54.000}{63} \\ &= 14.286 \;\; (\backslash\%)\end{aligned}$$

This solution is acceptable, but the voltage margin is limited.

Second proposition

EMHS101ARA331MMN0S aluminum electrolytic capacitors with Temp_max = 150°C, Below a screenshoot of the datasheet [4].

WV (V_{dc})	Cap (μF)	Size code	ESR (Ω max./100kHz)		Rated ripple current (mArms/125℃, 100kHz)	Part No.
			20℃	−40℃		
100	110	KE0	0.17	2.5	920	EMHS101□RA111MKE0S
	150	KG5	0.13	1.8	1,030	EMHS101□RA151MKG5S
	160	LH0	0.098	1.3	1,640	EMHS101□RA161MLH0S
	200	MH0	0.091	0.98	1,720	EMHS101□RA201MMH0S
	240	LN0	0.063	0.80	2,230	EMHS101□RA241MLN0S
	330	MN0	0.059	0.59	2,300	EMHS101□RA331MMN0S

Figure 2: EMHS101ARA331MMN0S aluminum electrolytic capacitors with Temp_max = 150°C

Let's start with a configuration of 10 capacitors in parallel, in the worst case ($C_{capa} = C_{min}$ of the datasheet)

$$\mathrm{Nb}_{capa} = 10$$

$$C_{capa_{nom}} = 330 \ \ (\mathrm{uF})$$

$$\mathrm{Margin} = 20 \ \ (\backslash\%)$$

$$C_{capa} = C_{capa_{nom}} \cdot \left(1 - \frac{\mathrm{Margin}}{100}\right) = 330 \cdot \left(1 - \frac{20}{100}\right) \qquad = 264.000 \ \ (\mathrm{uF, Worst\ case})$$

$$C_{eq} = C_{capa} \cdot \mathrm{Nb}_{capa} = 264.000 \cdot 10 \qquad = 2640.000 \ \ (\mathrm{uF} > 415\mathrm{uF\ ok})$$

$$\mathrm{ESR}_{capa} = 59 \ \ (\Omega\ @\ 100\mathrm{kHz})$$

$$\mathrm{ESR}_{eq} = \frac{\mathrm{ESR}_{capa}}{\mathrm{Nb}_{capa}} = \frac{59}{10} \qquad = 5.900 \ \ (\Omega > 3.18\mathrm{m\ NOK})$$

Since the ESR does not satisfy the 50%–50% condition of the formula, we must use the full (unsimplified) expression for the voltage ripple.

$$\mathrm{Icapa}_{max} = 2.300$$

$$\begin{aligned}\mathrm{Ieq}_{max} &= \mathrm{Icapa}_{max} \cdot \mathrm{Nb}_{capa} \\ &= 2.300 \cdot 10 \\ &= 23.000 \ \ (@\ \mathrm{Arms}\ @\ 125^\circ\mathrm{C}\ 100\mathrm{kHz} > 12.08\mathrm{Arms\ ok})\end{aligned}$$

I_rect_peak

$$I_{rect_{peak}} = \mathrm{Io} \cdot \frac{\pi}{2} = 25.000 \cdot \frac{3.142}{2} \qquad = 39.270 \ \ (\mathrm{A})$$

Voltage ripples

$$\begin{aligned}\Delta_{V_{out}} &= \sqrt{\left(\frac{\mathrm{Io}}{8 \cdot \mathrm{fsw}_{min} \cdot C_{eq} \cdot 1 \times 10^{-6}}\right)^2 + \left(\frac{\pi}{2} \cdot \mathrm{Io} \cdot \mathrm{ESR}_{eq} \cdot 1 \times 10^{-3}\right)^2} \\ &= \sqrt{\left(\frac{25.000}{8 \cdot 60170.000 \cdot 2640.000 \cdot 1 \times 10^{-6}}\right)^2 + \left(\frac{3.142}{2} \cdot 25.000 \cdot 5.900 \cdot 1 \times 10^{-3}\right)^2} \\ &= 0.233 \ \ (\mathrm{V} < 0.25\mathrm{V\ Ok})\end{aligned}$$

The condition is satisfied, but with a very limited margin.

Self heating

Power Dissipation of Each Capacitor

$$I_{each_{capa}} = \frac{I_{Co}}{\mathrm{Nb}_{capa}} = \frac{12.086}{10} \qquad = 1.209$$

$$\begin{aligned} P_{selfHeating} &= \mathrm{ESR}_{capa} \cdot 1 \times 10^{-3} \cdot \left(I_{each_{capa}}\right)^2 \\ &= 59 \cdot 1 \times 10^{-3} \cdot (1.209)^2 \\ &= 0.086 \ \ (\mathrm{W}) \end{aligned}$$

Estimation of Thermal Resistance Rth

$$\Delta_T = 150 - 125 \qquad = 25 \ \ (^\circ\mathrm{C})$$

$$\begin{aligned} P_{dissip} &= \mathrm{ESR}_{capa} \cdot 1 \times 10^{-3} \cdot (\mathrm{Icapa}_{max})^2 \\ &= 59 \cdot 1 \times 10^{-3} \cdot (2.300)^2 \\ &= 0.312 \ \ (\mathrm{W}) \end{aligned}$$

$$R_{th} = \frac{\Delta_T}{P_{dissip}} = \frac{25}{0.312} \qquad = 80.100 \ \ (^\circ\mathrm{C/W})$$

The self heating estimation and the max ambiant temp

$$\Delta_T = P_{selfHeating} \cdot R_{th} = 0.086 \cdot 80.100 \qquad = 6.903 \ \ (^\circ\mathrm{C} => \text{low delta temp})$$

$$\mathrm{Margin} = 30 \ \ (^\circ\mathrm{C})$$

$$T_{max} = 150$$

$$T_{amb_{max}} = T_{max} - \Delta_T - \mathrm{Margin} = 150 - 6.903 - 30 \qquad = 113.097 \ \ (^\circ\mathrm{C})$$

$$\mathrm{Vo}_{max} = 54.000 \ \ (\mathrm{VDC})$$

$$V_{max_{datasheet}} = 100 \ \ (\mathrm{VDC})$$

$$\mathrm{Voltage}_{Margin} = 100 \cdot \frac{V_{max_{datasheet}} - \mathrm{Vo}_{max}}{V_{max_{datasheet}}} = 100 \cdot \frac{100 - 54.000}{100} \qquad = 46.000 \ \ (\backslash\%)$$

Comparaison

	requirements	Solutio1	Solutio2
ESR_eq	3.18	2.83	5.90
C_eq	415.49	576.00	2640.00
Ieq_max	12.09	27.60	23.00
VmaxDC	54.00	63.00	100.00
Delta_V_out	0.25	0.14	0.23
C_capa	NaN	96.00	264.00
Nb_capa	NaN	6.00	10.00
P_selfHeating	NaN	0.07	0.09
T_amb_max	NaN	115.21	113.10
Voltage_Margin	NaN	14.29	46.00

*) The ESR requirement is based on the 50%–50% formula (see above for solution2).

The voltage margin in the first solution is limited (16% in the worst case). Nevertheless, I recommend proceeding with this option due to the number of parallel capacitors. Careful control is required to avoid overshoot or transient voltages, particularly when Vout is at its maximum.

Input Capacitor Ci

We will use the same formula as the output capacitor above:

Numerical Implementation of the Formulas 50% 50%

We must use fsw_min to the worst case

$$\mathrm{Ii} = \frac{\mathrm{Power}}{V_{In_{min}}} = \frac{1200.000}{360.000} = 3.333 \ \ \mathrm{(A)}$$

$$\mathrm{fsw}_{min} = 60170.000 \ \ \mathrm{(Hz)}$$

$$\delta_V = 1 \ \ (\backslash\%)$$

$$\mathrm{DV} = V_{In_{nom}} \cdot \frac{\delta_V}{100} = 380.000 \cdot \frac{1}{100} = 3.800 \ \ \mathrm{(vpp)}$$

$$\mathrm{Ci}_{min_{uF}} = 1 \times 10^6 \cdot \frac{\mathrm{Ii}}{4 \cdot \mathrm{fsw}_{min} \cdot \mathrm{DV}} = 1 \times 10^6 \cdot \frac{3.333}{4 \cdot 60170.000 \cdot 3.800} = 3.645 \ \ \mathrm{(uF)}$$

$$
\begin{aligned}
\mathrm{ESR}_{max_m} &= 1 \times 10^3 \cdot \frac{\mathrm{DV}}{\mathrm{Ii} \cdot \pi} \\
&= 1 \times 10^3 \cdot \frac{3.800}{3.333 \cdot 3.142} \\
&= 362.873 \quad (\mathrm{m}\Omega)
\end{aligned}
$$

$$
\begin{aligned}
I_{Ci} &= \mathrm{Ii} \cdot \sqrt{\frac{(\pi)^2}{8} - 1} \\
&= 3.333 \cdot \sqrt{\frac{(3.142)^2}{8} - 1} \\
&= 1.611 \quad (\mathrm{Arms})
\end{aligned}
$$

Film Capacitors MKP 1848e 4uF +/-5% 700V (MKP1848E54070JK2)

Let's start with this capacitor MKP1848E54070JK2 see the datasheet [5].

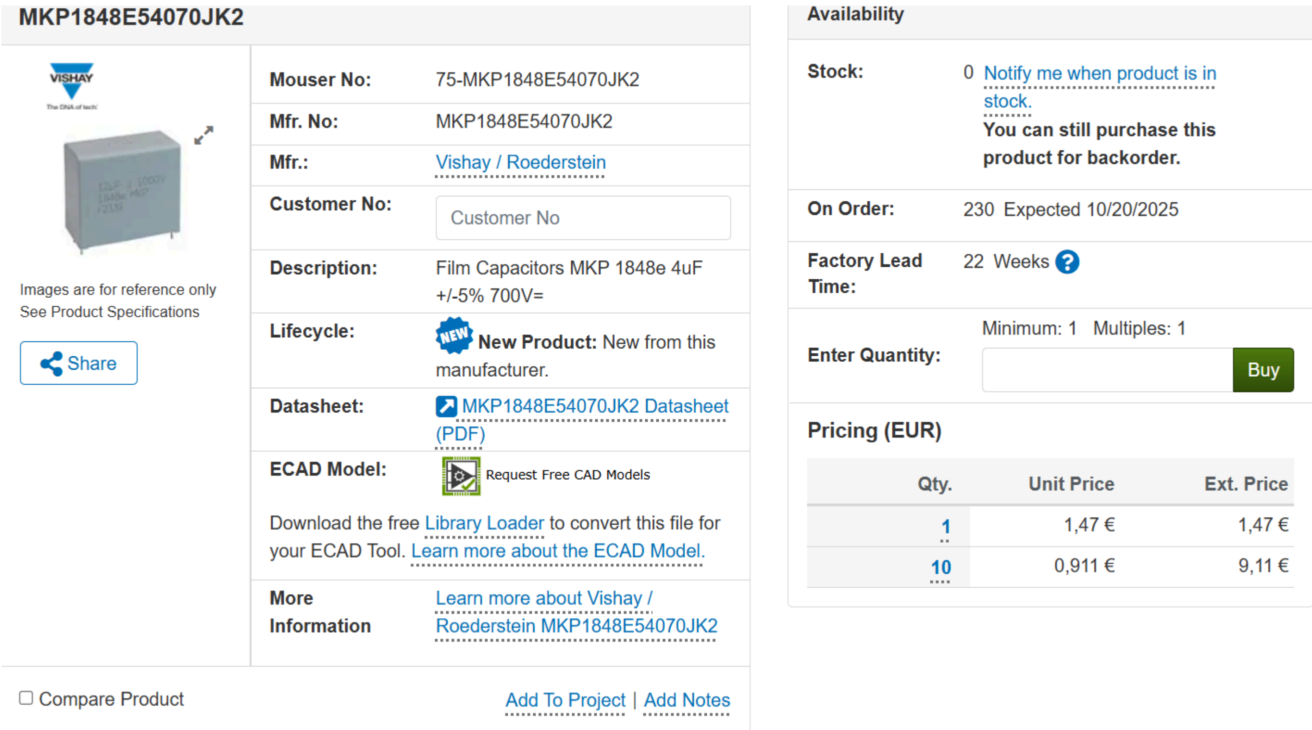


Figure 3: Mouser, Film Capacitors MKP 1848e 4uF +/-5% 700V (MKP1848E54070JK2)

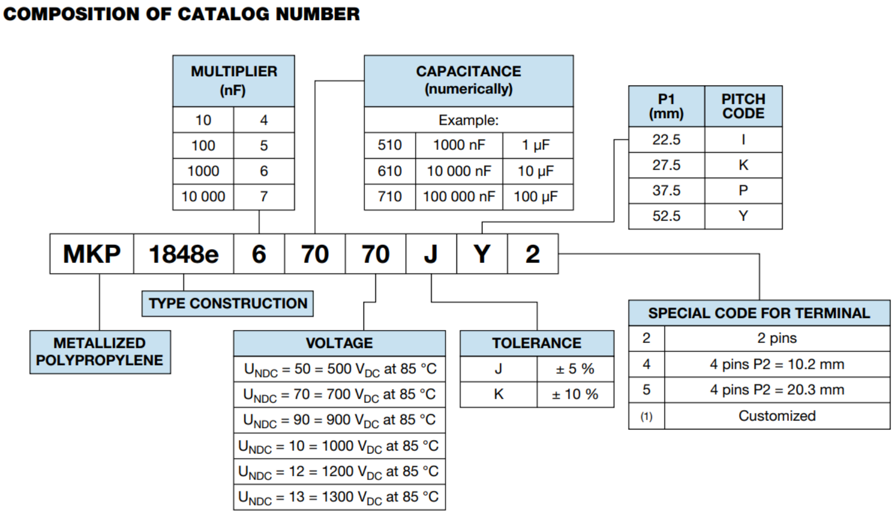
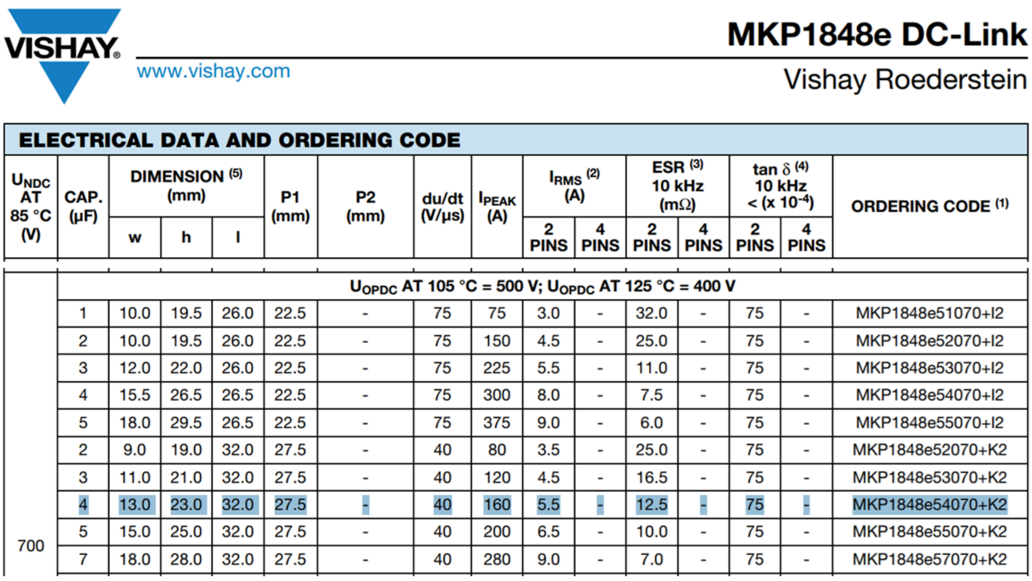


Figure 4: Understund the part number

Signification of the part number

	MKP1848E54070JK2
MKP	METALLIZED POLYPROPYLENE
1848E	TYPE CONSTRUCTION
5	MULTIPLIER (nF)=100
40	CAPACITANCE 40=4000nF
70	VOLTAGE UNDC = 70 = 700 VDC at 85 °C
J	TOLERANCE J=5%
K	Pitch code = K => P1=27.5mm
2	2 = 2pins



VISHAY.

MKP1848e DC-Link

www.vishay.com

Vishay Roederstein

ELECTRICAL DATA AND ORDERING CODE

U_{NDC} AT 85 °C (V)	CAP. (µF)	DIMENSION (5) (mm) w	h	l	P1 (mm)	P2 (mm)	du/dt (V/µs)	I_{PEAK} (A)	I_{RMS} (2) (A) 2 PINS	4 PINS	ESR (3) 10 kHz (mΩ) 2 PINS	4 PINS	tan δ (4) 10 kHz < (x 10^{-4}) 2 PINS	4 PINS	ORDERING CODE (1)
	U_{OPDC} AT 105 °C = 500 V; U_{OPDC} AT 125 °C = 400 V														
	1	10.0	19.5	26.0	22.5	-	75	75	3.0	-	32.0	-	75	-	MKP1848e51070+I2
	2	10.0	19.5	26.0	22.5	-	75	150	4.5	-	25.0	-	75	-	MKP1848e52070+I2
	3	12.0	22.0	26.0	22.5	-	75	225	5.5	-	11.0	-	75	-	MKP1848e53070+I2
	4	15.5	26.5	26.5	22.5	-	75	300	8.0	-	7.5	-	75	-	MKP1848e54070+I2
	5	18.0	29.5	26.5	22.5	-	75	375	9.0	-	6.0	-	75	-	MKP1848e55070+I2
	2	9.0	19.0	32.0	27.5	-	40	80	3.5	-	25.0	-	75	-	MKP1848e52070+K2
	3	11.0	21.0	32.0	27.5	-	40	120	4.5	-	16.5	-	75	-	MKP1848e53070+K2
	4	13.0	23.0	32.0	27.5	-	40	160	5.5	-	12.5	-	75	-	MKP1848e54070+K2
700	5	15.0	25.0	32.0	27.5	-	40	200	6.5	-	10.0	-	75	-	MKP1848e55070+K2
	7	18.0	28.0	32.0	27.5	-	40	280	9.0	-	7.0	-	75	-	MKP1848e57070+K2

Figure 5: datasheet MKP1848E54070JK2, ESR= 12.5mOhom @10 kHz, Irms= 5.5A (Maximum RMS current at 10 kHz, +85 °C, Δt = +15 °C)

Verification

$$\text{Tolerance} = 5 \;\; (\backslash\%)$$

$$C_{Datasheet} = 4 \;\; (\text{uF})$$

$$\text{Ci}_{min_{uF}} = 3.645$$

$$C_{Min} = C_{Datasheet} \cdot \left(1 - \frac{\text{Tolerance}}{100}\right) = 4 \cdot \left(1 - \frac{5}{100}\right) \qquad = 3.800 \;\; (\text{uF} > 3.645 \text{ uF})$$

$$\text{ESR}_{max_m} = 362.873$$

$$\text{ESR}_{Datasheet} = 12.500 \;\; (\text{mOhm} < 362\text{mOhm})$$

$$\begin{aligned}
\Delta_{V_{out}} &= \sqrt{\left(\frac{\text{Ii}}{8 \cdot \text{fsw}_{min} \cdot C_{Min} \cdot 1 \times 10^{-6}}\right)^2 + \left(\frac{\pi}{2} \cdot \text{Ii} \cdot \text{ESR}_{Datasheet} \cdot 1 \times 10^{-3}\right)^2} \\
&= \sqrt{\left(\frac{3.333}{8 \cdot 60170.000 \cdot 3.800 \cdot 1 \times 10^{-6}}\right)^2 + \left(\frac{3.142}{2} \cdot 3.333 \cdot 12.500 \cdot 1 \times 10^{-3}\right)^2} \\
&= 1.823 \;\; (\text{V})
\end{aligned}$$

$$\begin{aligned}
\delta_{V_{out}} &= 100 \cdot \frac{\Delta_{V_{out}}}{V_{In_{nom}}} \\
&= 100 \cdot \frac{1.823}{380.000} \\
&= 0.480 \;\; (\backslash\% < 1\backslash\% \text{ Ok})
\end{aligned}$$

Impedance curve

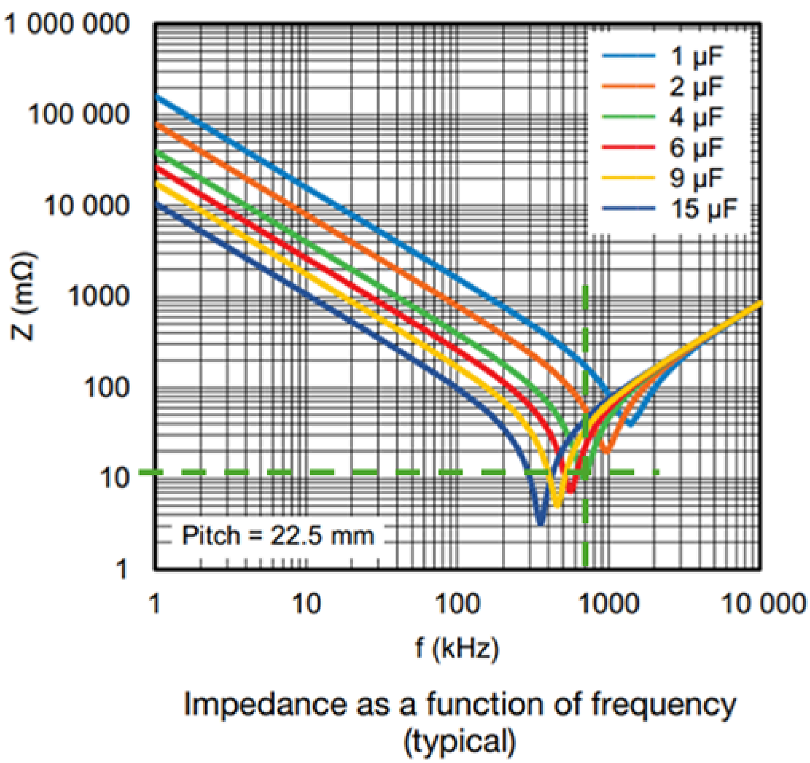


Figure 6: datasheet 700V 4uF, ESR ~ 12mOhm, Fres = 700kHz

Estimation of the ESL

$$C = 4 \quad (\text{uF})$$

$$\text{Fres} = 700000.000 \quad (\text{Hz})$$

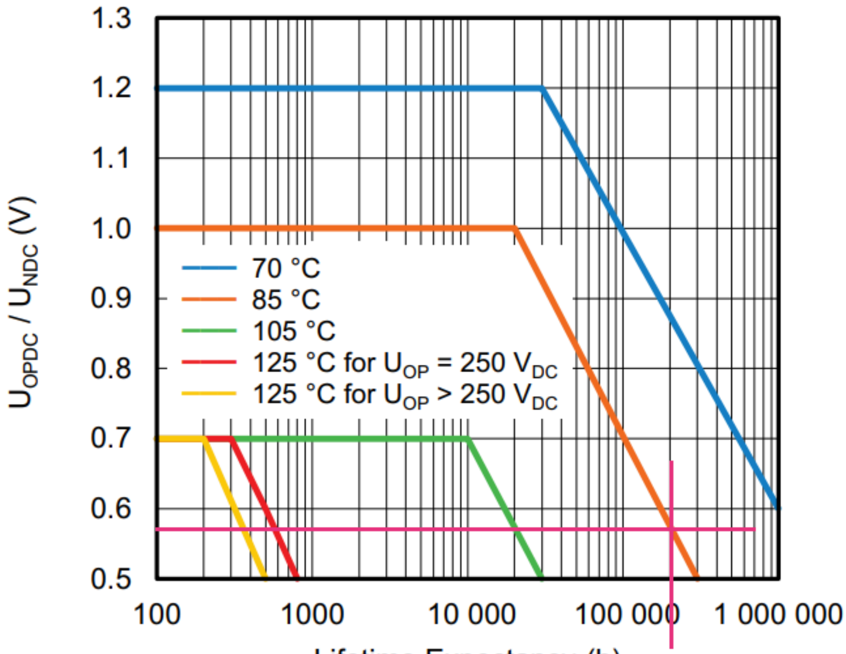
$$\text{ESL} = \frac{1 \times 10^9}{(2 \cdot \pi \cdot \text{Fres})^2 \cdot C \cdot 1 \times 10^{-6}} = \frac{1 \times 10^9}{(2 \cdot 3.142 \cdot 700000.000)^2 \cdot 4 \cdot 1 \times 10^{-6}} = 12.924 \quad (\text{nH})$$

Expectation life time

$$U_{OPDC} = 400 \quad (\text{Operation dc voltage})$$

$$U_{NDC} = 700 \quad (\text{Nominal dc voltage})$$

$$k = \frac{U_{OPDC}}{U_{NDC}} = \frac{400}{700} = 0.571$$



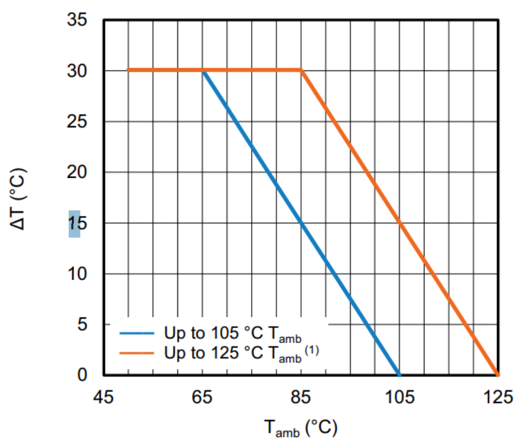
Lifetime expectancy
(typical)

Figure 7: Life time expectancy (h), k = 0.57, Tamb = 85°C ==> 200 000 h

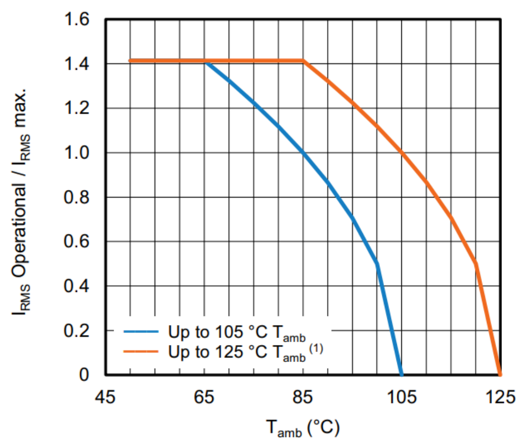
$$\text{Life}_h = 200000 \quad \text{(hours)}$$

$$\text{Life}_{years} = 22.831 \quad \text{(Years)}$$

Tamb and current limit



Maximum allowed component temperature rise (ΔT)
as function of ambient temperature (T_{amb})



Maximum I_{RMS} current in function of the ambient temperature
(typical curve). Above 85 °C ambient temperature voltage derating
must be applicable

Figure 8: For 105°C curve, and 85°C amb, no limite in the rms current, coef = 1

The self heating

From the datasheet

$$\mathrm{ESR} = 12.500 \ \ (\mathrm{mOhm})$$

$$\mathrm{Icapa}_{rms} = 5.500 \ \ (\mathrm{Arms})$$

$$\Delta_T = 15 \ \ (^\circ\mathrm{C})$$

Selg heating

$$\mathrm{Pd} = \mathrm{ESR} \cdot 1 \times 10^{-3} \cdot (\mathrm{Icapa}_{rms})^2 = 12.500 \cdot 1 \times 10^{-3} \cdot (5.500)^2 \qquad = 0.378 \ \ (\mathrm{W})$$

$$\mathrm{Rth} = \frac{\Delta_T}{\mathrm{Pd}} = \frac{15}{0.378} \qquad = 39.669 \ \ (^\circ\mathrm{C/W})$$

Maximum permissible ambient temperature in the application

$$I_{Ci} = 1.611 \ \ (\text{the RMS current in our application})$$

$$\mathrm{Pd} = (I_{Ci})^2 \cdot \mathrm{ESR} \cdot 1 \times 10^{-3} = (1.611)^2 \cdot 12.500 \cdot 1 \times 10^{-3} \qquad = 0.032 \ \ (\mathrm{W})$$

$$\Delta_T = \mathrm{Rth} \cdot \mathrm{Pd} = 39.669 \cdot 0.032 \qquad = 1.288 \ \ (^\circ\mathrm{C})$$

$$T_{capaMax} = 105 \ \ (^\circ\mathrm{C})$$

$$\mathrm{Margin} = 10 \ \ (^\circ\mathrm{C})$$

$$T_{ambMax} = T_{capaMax} - \Delta_T - \mathrm{Margin} = 105 - 1.288 - 10 \qquad = 93.712$$

Resonanat capacitor Cr

Chosing a capacitor for Cr

The inputs data

$$\mathrm{Cr}_{nF} = 116.209 \ \ (\mathrm{nF})$$

$$V_{In_{max}} = 400.000 \ \ (\mathrm{V})$$

$$\mathrm{fsw}_{min} = 60170.000 \ \ (\mathrm{Hz})$$

The RMS voltage of the resonant capacitor

$$\begin{aligned} X_{Cr} &= \frac{1}{2 \cdot \pi \cdot \mathrm{fsw}_{min} \cdot \mathrm{Cr}_{nF} \cdot 1 \times 10^{-9}} \\ &= \frac{1}{2 \cdot 3.142 \cdot 60170.000 \cdot 116.209 \cdot 1 \times 10^{-9}} \\ &= 22.761 \ \ (\mathrm{Ohm}) \end{aligned}$$

$$V_{Cr} = \mathrm{Ir}_{rms} \cdot X_{Cr} = 10.354 \cdot 22.761 \qquad = 235.672 \ \ (\mathrm{V})$$

$$V_{Cr_{rms}} = \sqrt{\left(\frac{V_{In_{max}}}{2}\right)^2 + (V_{Cr})^2} = \sqrt{\left(\frac{400.000}{2}\right)^2 + (235.672)^2} \qquad = 309.098 \ \ (\mathrm{vrms})$$

Starting with the **B3267*L** film capacitors, the maximum rated DC voltage is 2000 V. [2].

```
The design value of Cr is 116.2 nF
Below are some possible combinations for constructing this resonant capacitor:
```

	Nominal_capa_nF	Nb capas in parallel	total capa nF	error %
0	6.2	19	117.8	1.4
1	6.8	17	115.6	-0.5
2	8.2	14	114.8	-1.2
3	10.0	12	120.0	3.3
4	12.0	10	120.0	3.3
5	15.0	8	120.0	3.3
6	22.0	5	110.0	-5.3
7	33.0	4	132.0	13.6
8	47.0	2	94.0	-19.1
9	56.0	2	112.0	-3.6
10	68.0	2	136.0	17.0

The current of each element capacitor

$$\mathrm{Ir}_{rms_1} = 1.294$$

The 15 nF, 15 mm, 2000 VDC TDK MKP capacitor meets both the Vrms and Irms requirements.

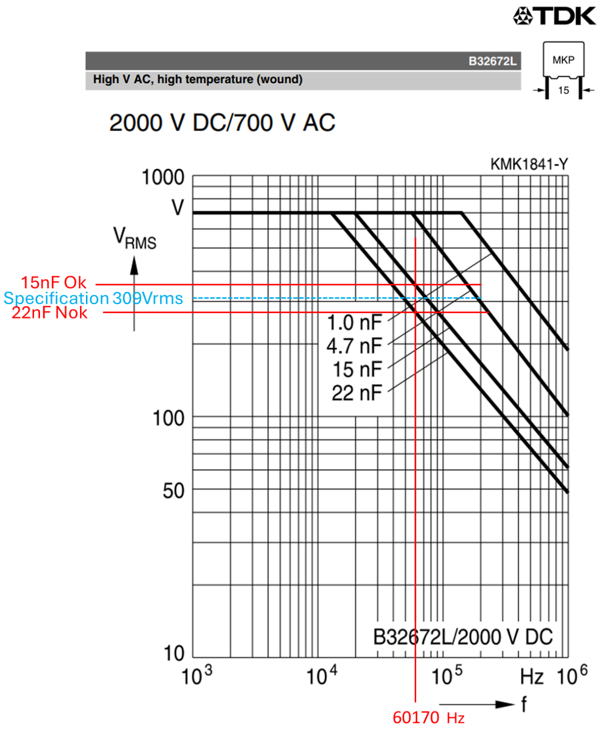


Figure 9: Vrms 15 nF, 15 mm, 2000 VDC TDK MKP

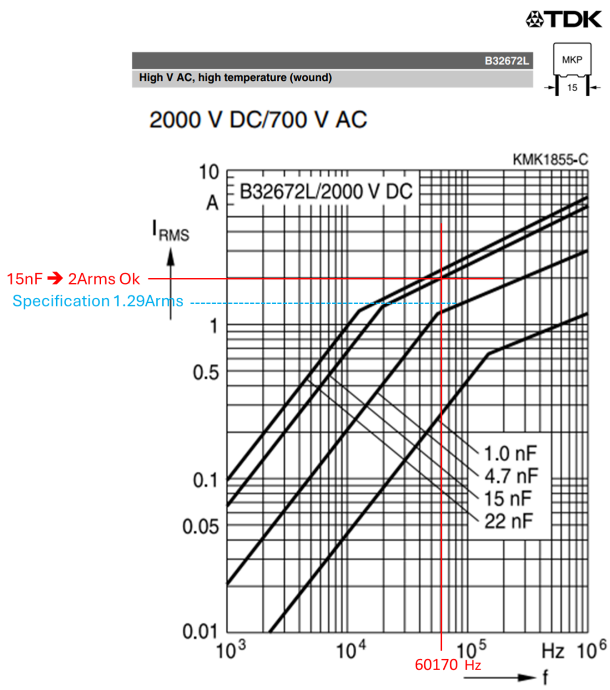


Figure 10: Irms 15 nF, 15 mm, 2000 VDC TDK MKP

Below is a screenshot from the B32672L datasheet. The ref **B32672L8153** is a 15 nF capacitor.

B32672L

High V AC, high temperature (wound)

MKP 15

Ordering codes and packing units (lead spacing 15 mm)

V_{RMS} f ≤1 kHz V AC	V_R V DC	C_R nF	Max. dimensions w × h × l mm	Ordering code (composition see below)	Ammo pack pcs./MOQ	Reel pcs./MOQ	Untaped pcs./MOQ
700	2000	1.0	5.0 × 10.5 × 18.0	B32672L8102+***	4680	5200	4000
		1.2	5.0 × 10.5 × 18.0	B32672L8122+***	4680	5200	4000
		1.5	5.0 × 10.5 × 18.0	B32672L8152+***	4680	5200	4000
		2.2	5.0 × 10.5 × 18.0	B32672L8222+***	4680	5200	4000
		2.7	5.0 × 10.5 × 18.0	B32672L8272+***	4680	5200	4000
		3.3	5.0 × 10.5 × 18.0	B32672L8332+***	4680	5200	4000
		3.9	5.0 × 10.5 × 18.0	B32672L8392+***	4680	5200	4000
		4.7	5.0 × 10.5 × 18.0	B32672L8472+***	4680	5200	4000
		5.6	6.0 × 11.0 × 18.0	B32672L8562+***	3840	4400	4000
		6.2	6.0 × 11.0 × 18.0	B32672L8622+***	3840	4400	4000
		6.8	6.0 × 11.0 × 18.0	B32672L8682+***	3840	4400	4000
		8.2	6.0 × 12.0 × 18.0	B32672L8822+***	3840	4400	4000
		10	7.0 × 12.5 × 18.0	B32672L8103+***	3320	3600	4000
		12	8.5 × 14.5 × 18.0	B32672L8123+***	2720	2800	2000
		15	8.5 × 14.5 × 18.0	B32672L8153+***	2720	2800	2000
		22	9.0 × 17.5 × 18.0	B32672L8223+***	2560	2800	2000
		33	11.0 × 18.5 × 18.0	B32672L8333+***	–	2200	1200

Figure 11: B32672L8153 is a 15 nF capacitor.

The ESR and Power dissipation

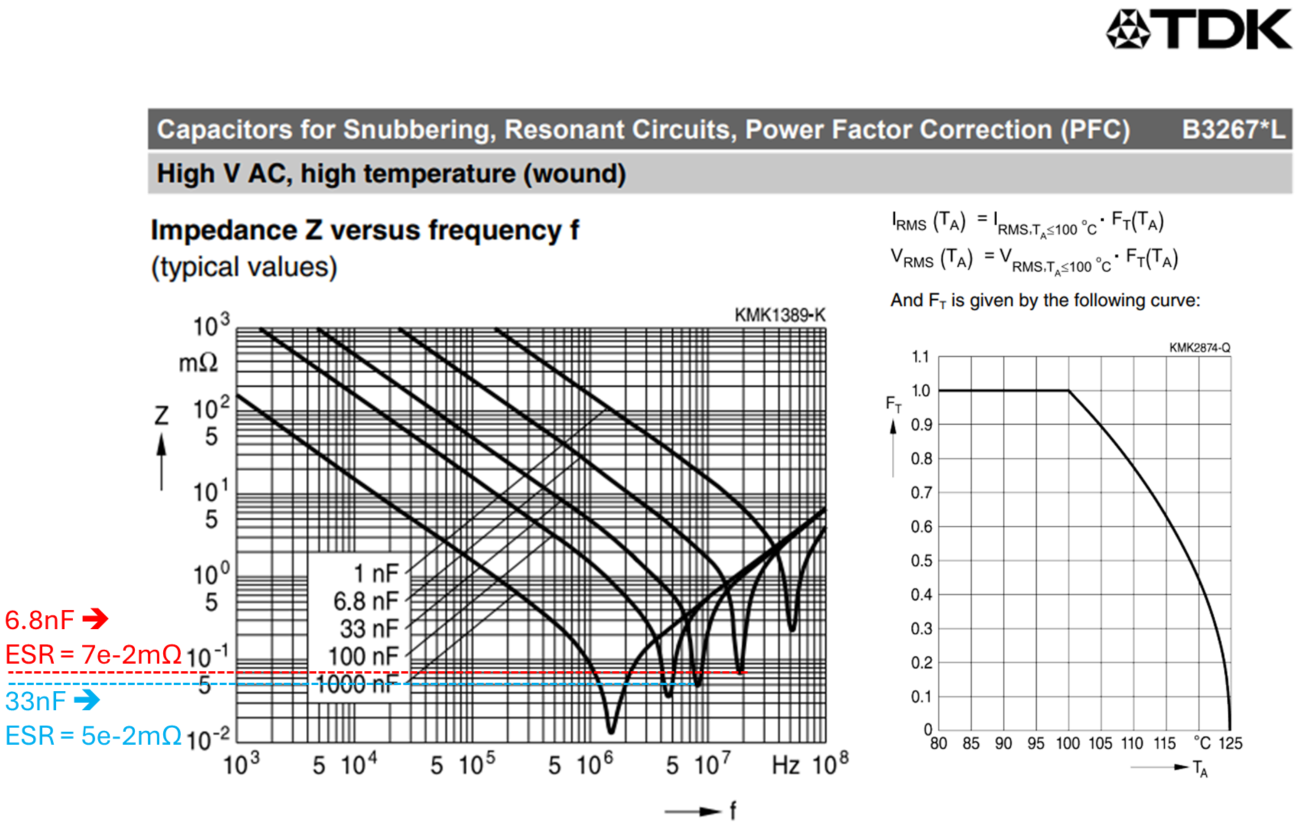


Figure 12: ESR and Thermal derating

From the below

6.8nF ESR=70μΩ

33nF ESR=50μΩ

By linear interpolation, the ESR of a 15 nF capacitor can be estimated as 63.74 μΩ

The power dissipation of each capacitor

$$\mathrm{ESR}_u = 63.740 \quad (\mu\Omega)$$

$$\mathrm{Ir}_{rms_1} = 1.294 \quad (\mathrm{Arms})$$

$$\mathrm{Ir}_{rms_{max}} = 2 \quad (\mathrm{Arms})$$

$$\mathrm{PD}_{uW} = \mathrm{ESR}_u \cdot (\mathrm{Ir}_{rms_1})^2 = 63.740 \cdot (1.294)^2 \qquad = 106.771 \quad (\mathrm{uW})$$

The Rth estimation

$$T_{max} = 125$$

$$T_{100} = 100$$

$$\Delta_T = T_{max} - T_{100} = 125 - 100 \qquad = 25$$

$$\mathrm{PD}_{uW_{max}} = \mathrm{ESR}_u \cdot (\mathrm{Ir}_{rms_{max}})^2 = 63.740 \cdot (2)^2 \qquad = 254.962$$

$$R_{TH} = \frac{\Delta_T}{\mathrm{PD}_{uW_{max}}} = \frac{25}{254.962} \qquad = 0.098 \;\; (^\circ \mathrm{C/uW})$$

Each capacitor's self-heating and the maximum permissible ambient temperature.

$$\Delta_T = \mathrm{PD}_{uW} \cdot R_{TH} = 106.771 \cdot 0.098 \qquad = 10.469 \;\; (^\circ \mathrm{C})$$

$$T_{amb_{max}} = 125 - \Delta_T = 125 - 10.469 \qquad = 114.531 \;\; (^\circ \mathrm{C})$$

Understanding the Derating Curve of the Capacitors

One point calculation

$$\mathrm{Ta} = 105$$

$$\Delta_T = T_{max} - \mathrm{Ta} = 125 - 105 \qquad = 20$$

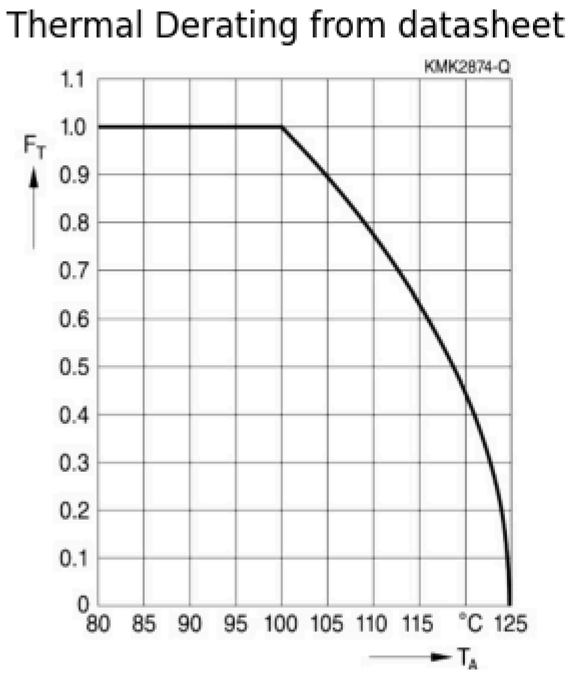
$$\mathrm{PD}_{uW_{max}} = \frac{\Delta_T}{R_{TH}} = \frac{20}{0.098} \qquad = 203.969$$

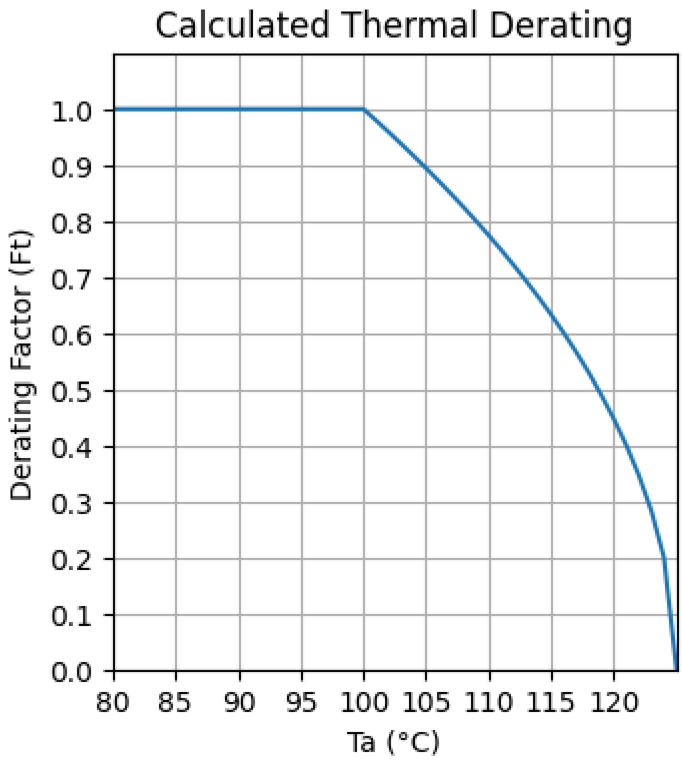
$$\mathrm{Ir}_{rms_{max_{Ta}}} = 1.789$$

$$\mathrm{Fa} = \frac{\mathrm{Ir}_{rms_{max_{Ta}}}}{\mathrm{Ir}_{rms_{max}}} = \frac{1.789}{2} \qquad = 0.894$$

The same calculation is repeated to construct the derating curve.

```
(80.0, 125.0)
```





Resonant capacitors configuration

There are two possible configurations for the resonant capacitors:

- All capacitors in parallel:

which is the classic LLC configuration and offers simplicity in layout.

- Dividing the capacitors between the high side and low side:

which helps balance HV+ and HV-.

Below is a simulation of both solutions. We can see that the voltage and current of each capacitor are almost identical in both configurations, and all other voltages and currents are also very similar.

You can donwload the LTSPICE file using this Link.

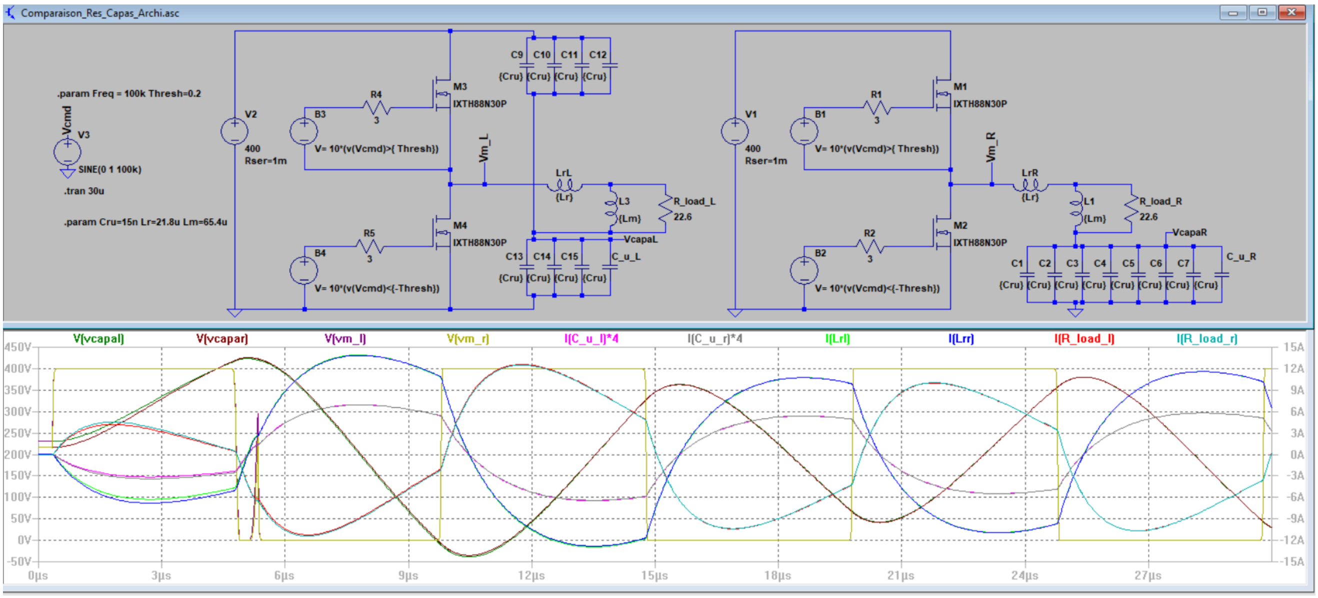


Figure 13: Simulation of resonant capacitor configurations

Bill of Materials (BOM) of this part

	Mouser No	Mfr. No	Number	componenent	remark
0	871-B40910A8127M000	B40910A8127M000	6	Output capa	Alum capa - SMD 63VDC 120uF (M) d10x125 mm SMD HP
1	75-MKP1848E54070JK2	MKP1848E54070JK2	1	Input capa	Film Capacitors MKP 1848e 4uF +/-5% 700V
2	871-B32672L8153J	B32672L8153J	8	Resonant capa	Film Cap 15NF 5% 700VAC MKP BOXED

References

[1] Hong Huang, *Designing an LLC Resonant Half-Bridge Power Converter*. Available: https://bbs.dianyuan.com/upload/community/2013/12/01/1385867010-65563.pdf

[2] B40910 Aluminum electrolytic capacitors datasheet

[3] B3267*L Film Capacitors

[4] EMHS Aluminum electrolytic capacitors datasheet

[5] Film Capacitors MKP 1848e 4uF +/-5% 700V datasheet , MKP1848E54070JK2