Resonance Tank Capacitor and Output Capacitor

Inputs and claculated parameters

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

	Output datas
Lnc	3.000000e+00
Qec	5.500000e-01
Cr_nF	1.162090e+02
n	4.000000e+00
Lr_uH	2.179700e+01
Lm_uH	6.539200e+01
fsw_min	6.017000e+04
fsw_max	1.562200e+05
Im_rms	6.992000e+00
Io	2.500000e+01
Ioe_rms	7.636000e+00
Ios_rms	3.054500e+01
Ir_rms	1.035400e+01
L_second_uH	4.087000e+00
Re_nom	2.490100e+01
Re_110	2.263700e+01
Cr	1.162090e-07
Lr	2.179700e-05
Lm	6.539200e-05

Output capacitor Co

Formulas

For a resistive load, the output capacitor is determined by

$$C_o \geq C_{o_{min}} = \frac{I_o}{8 \cdot f_{sw} \cdot \Delta V_{out}}$$

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)

$$ESR_{max} = \frac{\Delta V_{out}}{I_{rect\_peak}} = \frac{\Delta V_{out}}{\frac{\pi}{4} \cdot I_o \cdot 2}$$

$$I_{C_o} = I_o \sqrt{\frac{\pi^2}{8} - 1}$$

Where:

- I_{C_o} : RMS current of the capacitor @ f_sw = f_nom

See page 26, 27 [1].
By default, you can found all formula of this chapeter in the same ref

Numerical Implementation of the Formulas

We must use fsw_min to the worst case

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

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

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

$$\mathrm{Co}_{min_{uF}} = 1 \times 10^6 \cdot \frac{\mathrm{Io}}{8 \cdot \mathrm{fsw}_{min} \cdot \mathrm{DV}} = 1 \times 10^6 \cdot \frac{25.000}{8 \cdot 60170.000 \cdot 0.250} = 207.745 \ \ (\mathrm{uF})$$

$$\mathrm{ESR}_{max_m} = 1 \times 10^3 \cdot \frac{\mathrm{DV}}{\mathrm{Io} \cdot \frac{\pi}{2}} = 1 \times 10^3 \cdot \frac{0.250}{25.000 \cdot \frac{3.142}{2}} = 6.366 \ \ (\mathrm{m}\Omega)$$

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

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: VRMS

Let's start with a configuration of 5 capacitors in parallel

$$\mathrm{Nb}_{capa} = 5$$

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

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

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

$$C_{eq} = C_{capa} \cdot \mathrm{Nb}_{capa} = 96.000 \cdot 5 \qquad = 480.000 \ \ (\mathrm{uF} > 208$$

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

$$\mathrm{ESR}_{eq} = \frac{\mathrm{ESR}_{capa}}{\mathrm{Nb}_{capa}} = \frac{17}{5} \qquad = 3.400 \ \ (\Omega < 6.36$$

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

$$\mathrm{Ieq}_{max} = \mathrm{Icapa}_{max} \cdot \mathrm{Nb}_{capa} = 4.600 \cdot 5 \qquad = 23.000 \ \ (@ \ \mathrm{Arms} \ @ \ 125^\circ\mathrm{C} \ 100\mathrm{kHz} > 12.08\mathrm{Ar}$$

Voltage ripples

$$\Delta_{V_{out}} = \frac{\mathrm{Io}}{8 \cdot \mathrm{fsw}_{min} \cdot C_{eq} \cdot 1 \times 10^{-6}} = \frac{25.000}{8 \cdot 60170.000 \cdot 480.000 \cdot 1 \times 10^{-6}} \qquad = 0.108$$

Self heating

Power Dissipation of Each Capacitor

$$I_{each_{capa}} = \frac{I_{Co}}{\text{Nb}_{capa}} = \frac{12.086}{5} \qquad = 2.417$$

$$\begin{aligned} P_{selfHeating} &= \text{ESR}_{capa} \cdot 1 \times 10^{-3} \cdot \left(I_{each_{capa}}\right)^2 \\ &= 17 \cdot 1 \times 10^{-3} \cdot (2.417)^2 \\ &= 0.099 \ \ (\text{W}) \end{aligned}$$

Estimation of Thermal Resistance Rth

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

$$\text{ESR} = 0.017$$

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

$$P_{dissip} = \text{ESR} \cdot (I)^2 = 0.017 \cdot (4.600)^2 \qquad = 0.360 \ \ (\text{W})$$

$$R_{th} = \frac{\Delta_T}{P_{dissip}} = \frac{25}{0.360} \qquad = 69.498 \ \ (^\circ\text{C/W})$$

The self heating estimation and the max ambiant temp

$$\Delta_T = P_{selfHeating} \cdot R_{th} = 0.099 \cdot 69.498 \qquad = 6.903 \ \ (^\circ\text{C} => \text{low delta temp})$$

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

$$T_{max} = 150$$

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

Voltage margin

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

$$V_{max_{datasheet}} = 63 \ \ (\text{VDC})$$

$$\text{Voltage}_{Margin} = 100 \cdot \frac{V_{max_{datasheet}} - \text{Vo}_{max}}{V_{max_{datasheet}}} = 100 \cdot \frac{63 - 54.000}{63} \qquad = 14.286 \ \ (\backslash\%)$$

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 (Vdc)	Cap (μF)	Size code	ESR (Ω max./100kHz) 20℃	ESR (Ω max./100kHz) −40℃	Rated ripple current (mArms/125℃, 100kHz)	Part No.
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: VRMS

Let's start with a configuration of 5 capacitors in parallel

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

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

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

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

$$C_{eq} = C_{capa} \cdot \mathrm{Nb}_{capa} = 264.000 \cdot 10 \qquad = 2640.000 \ \ (\mathrm{uF} > 208$$

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

$$\mathrm{ESR}_{eq} = \frac{\mathrm{ESR}_{capa}}{\mathrm{Nb}_{capa}} = \frac{59}{10} \qquad = 5.900 \ \ (\Omega < 6.36$$

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

$$\mathrm{Ieq}_{max} = \mathrm{Icapa}_{max} \cdot \mathrm{Nb}_{capa} = 2.300 \cdot 10 \qquad = 23.000 \ \ (@ \ \mathrm{Arms} \ @ \ 125^{\circ}\mathrm{C} \ 100\mathrm{kHz} > 12.08\mathrm{Ar}$$

Voltage ripples

$$\Delta_{V_{out}} = \frac{\mathrm{Io}}{8 \cdot \mathrm{fsw}_{min} \cdot C_{eq} \cdot 1 \times 10^{-6}} = \frac{25.000}{8 \cdot 60170.000 \cdot 2640.000 \cdot 1 \times 10^{-6}} \qquad = 0.020$$

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	6.37	3.40	5.90
C_eq	207.74	480.00	2640.00
Ieq_max	12.09	23.00	23.00
VmaxDC	54.00	63.00	100.00
Delta_V_out	0.25	0.11	0.02
C_capa	NaN	96.00	264.00
Nb_capa	NaN	5.00	10.00
P_selfHeating	NaN	0.10	0.09
T_amb_max	NaN	113.10	113.10
Voltage_Margin	NaN	14.29	46.00

The margin in the first solution is limited (16% in the worst case). However, I propose we proceed with this option, given the number of parallel capacitors. Care must be taken in control to prevent any overshoot or transient voltage, especially when Vout is at Vout_max.

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

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

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

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

{ "Cr_nF": Cr_nF, "V_In_max": V_In_max, "fsw_min":fsw_min, "V_Cr_rms":V_Cr_rms, "Ir_rms":Ir_rms, }

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.

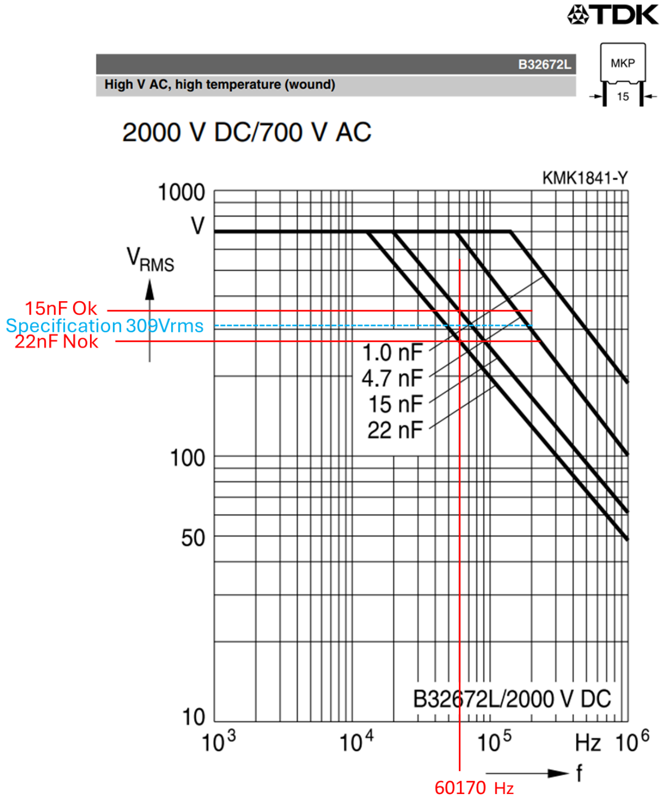


Figure 3: VRMS

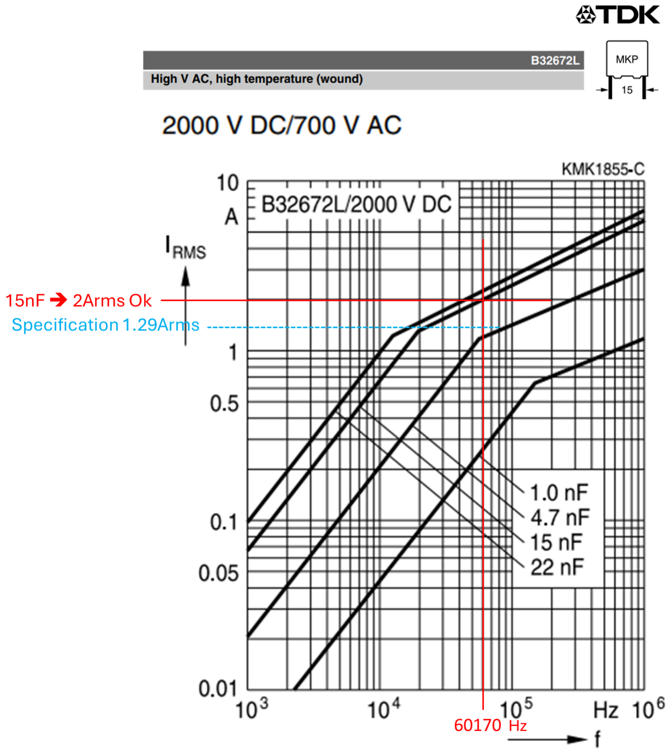


Figure 4: IRMS

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} $f \leq 1$ 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 5: VRMS

The ESR and Power dissipation

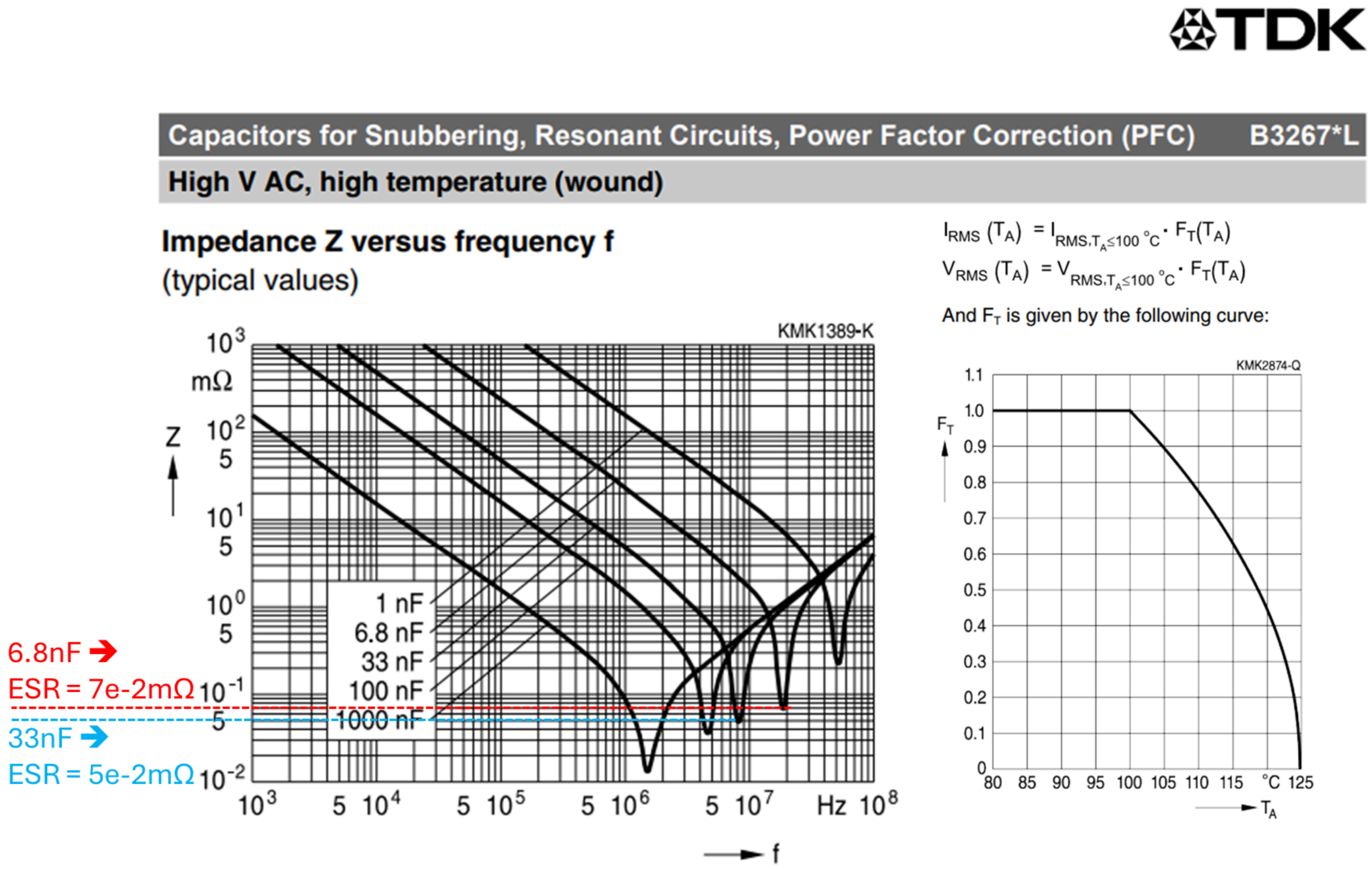


Figure 6: VRMS

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

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

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

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

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

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.

$$\Delta_T = \mathrm{PD}_{uW} \cdot R_{TH} = 106.771 \cdot 0.098 \qquad = 10.469$$

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

Understanding the Derating Curve of the Capacitors

One point calculation

$$\mathrm{Ta} = 105$$

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

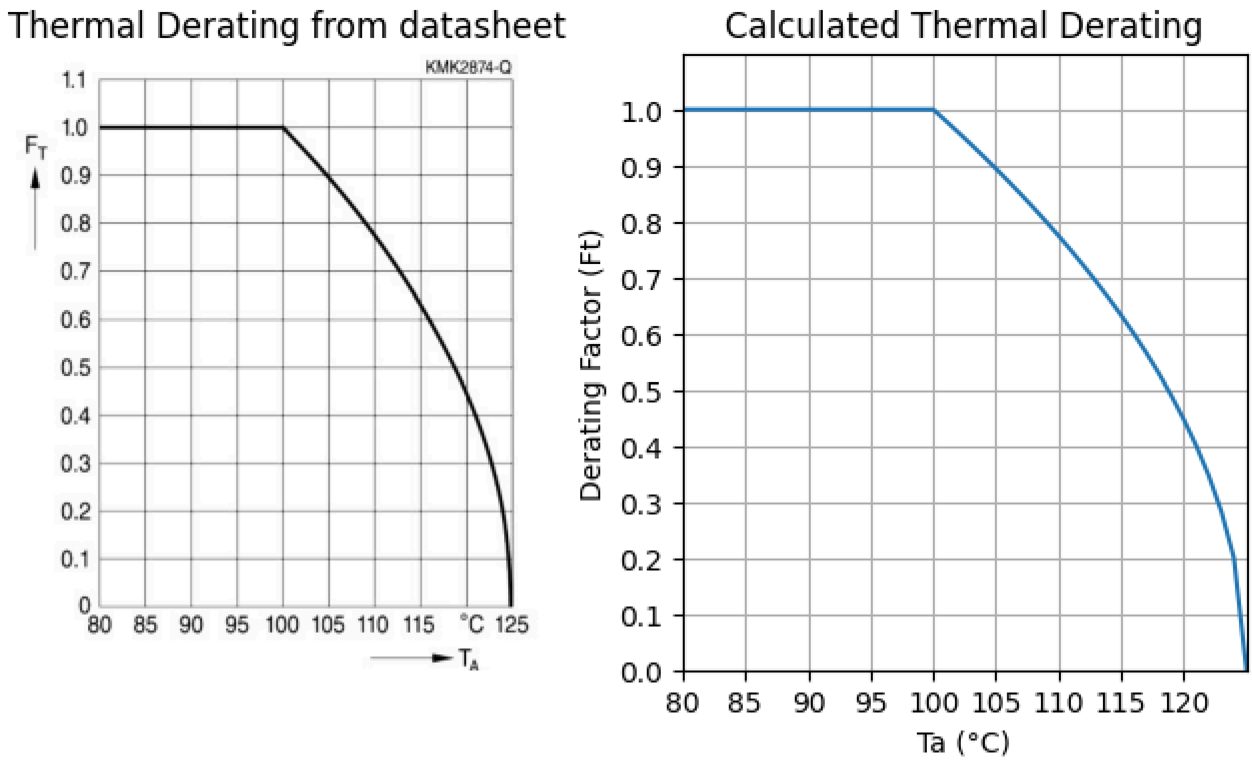
$$\mathrm{PD}_{uW_{max}} = \frac{\Delta_T}{R_{TH}} = \frac{20}{0.098} \qquad = 203.969$$

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

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

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.

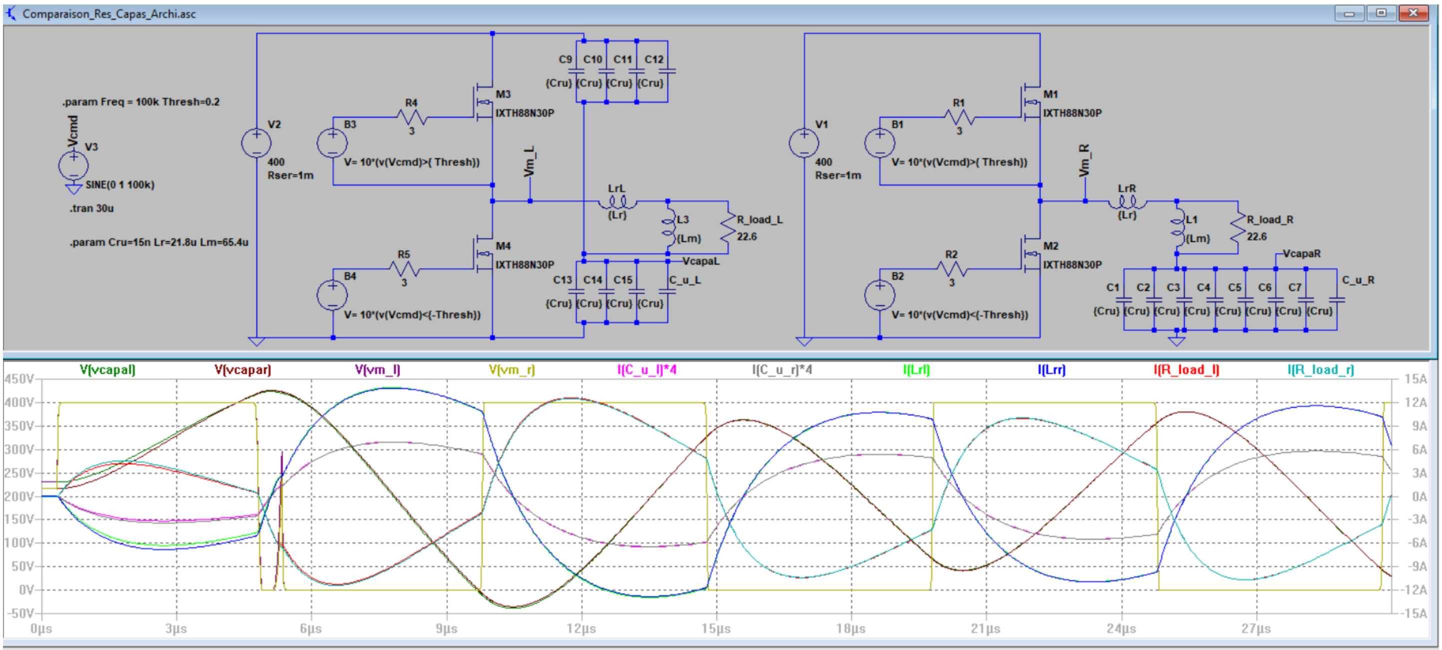


Figure 7: VRMS

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