The Multinational Power Electronics Association

PSMA PELS Capacitor Workshop
Rating MLCCs for AC Applications

John Bultitude, March 19, 2022

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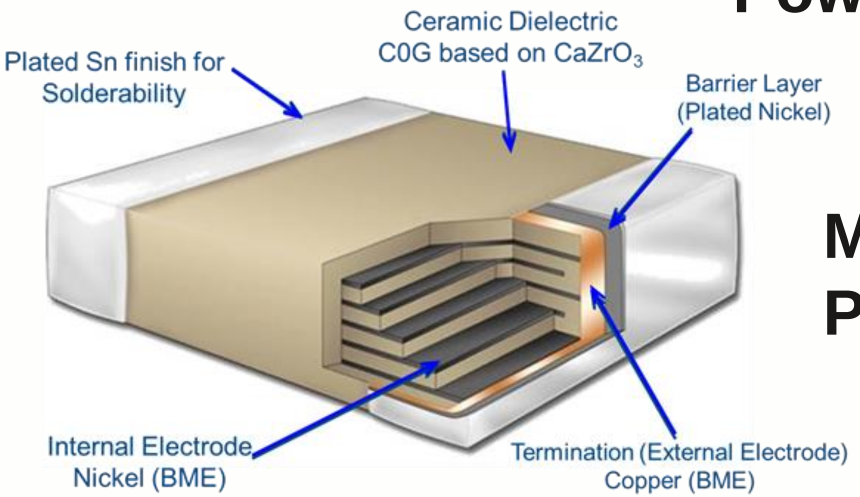
Presentation Outline

New Products

Power Application Trends



Electrothermal Models

MLCC Materials & Performance for Power

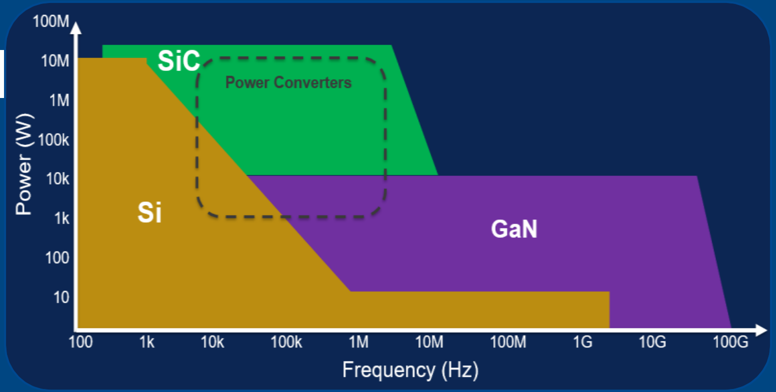
External Factors Affecting Performance

AC Performance Considerations

- **High AC Voltages**
- **I^2R Heating**

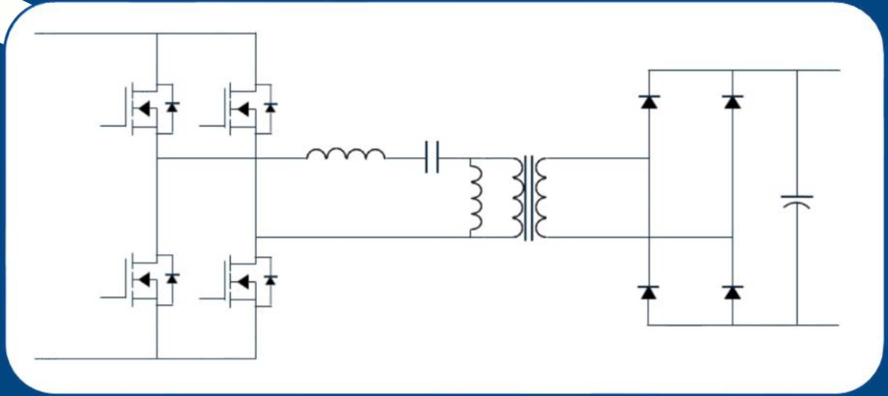
Power Application Trends

Wide Bandgap (WBG)

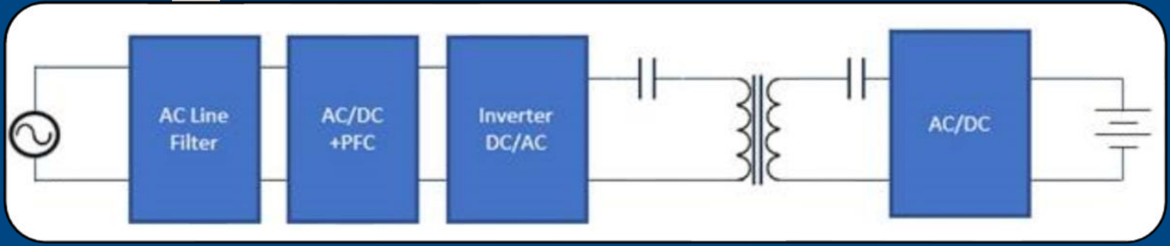


(10kHz- > 1MHz)

LLC Resonant Converters

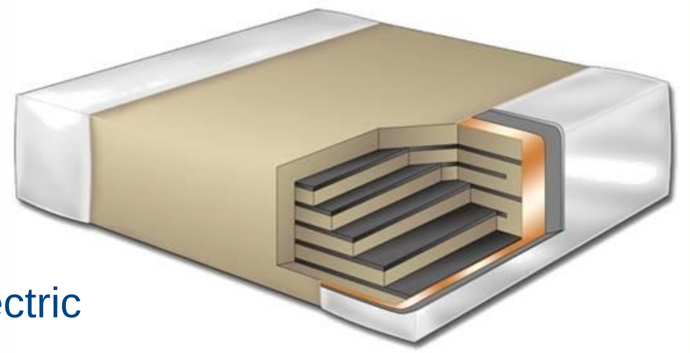


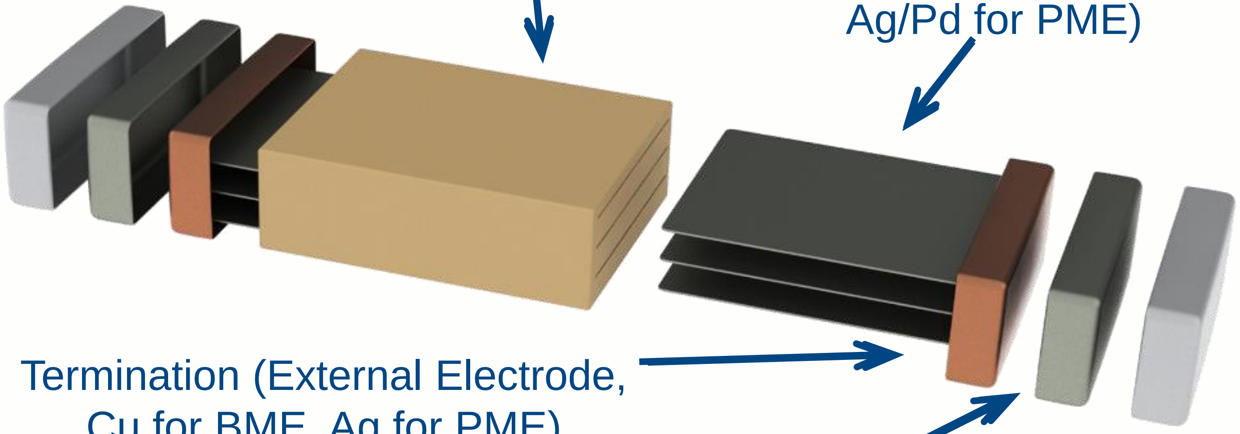
Resonant Wireless (~ 85kHz)
Power Transfer (WPT)

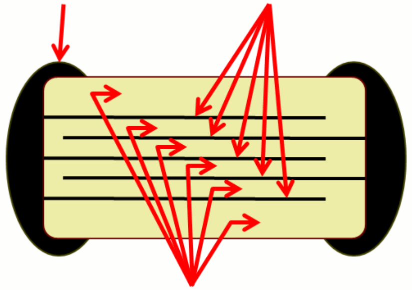


Capacitor Basics

MLCC Materials & Performance







Capacitance $C = \dfrac{\epsilon_0 KA(n-1)}{t}$

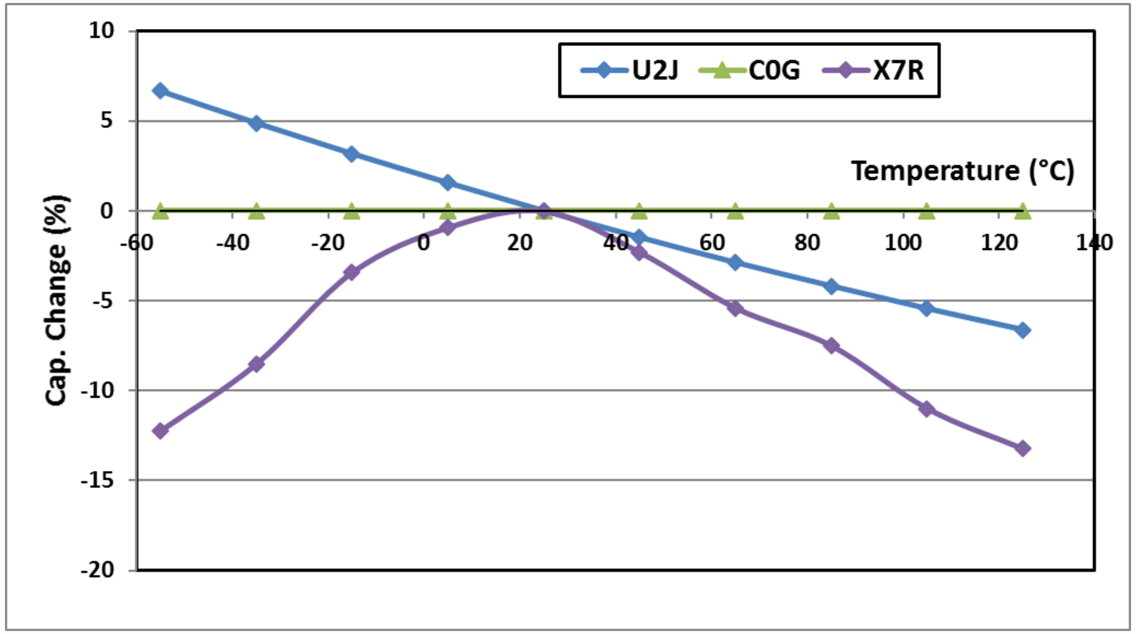
- **C** = Design Capacitance
- **K** = Dielectric Constant
- **A** = Overlap Area
- **t** = Ceramic thickness
- **n** = Number of electrodes
- ϵ_0 = **Permittivity of free space (8.854×10^{-12} F/m)**

Class I Vs Class II MLCCs

Class I Paraelectric low K, Examples C0G & U2J

Class II Ferroelectric high K, Example X7R

- Change of capacitance with temperature -55 to +125ºC (Ref 25ºC) is a key characteristic:
  - **X7R +/- 15%**
  - **C0G +/- 30 ppm/ºC**
  - **U2J −750 ±120 ppm/°C**
- X7R MLCCs capacitance is reduced further at high AC & DC voltages
- Some typical values & voltage ratings of KEMET Ni compatible dielectrics are shown in the table



Dielectric	K	DF	Rated DC
X7R	2400-3700	> 1%	6.3 – 3000V
C0G	31	< 0.1%	6.3 – 10,000V
U2J	82	< 0.1%	6.3 – 100V

Class I Vs Class II MLCCs

Attributes for Power Applications

Capacitor Requirements / Attributes	Wide Bandgap		LLC	Resonant Wireless Power Transfer	Class I BME C0G	Class II BME X7R
	DC-LINK	Snubber				
Capacitance Density	●	○	○	○	○	●
Capacitance Stability vs Temperature	○	○	●	●	●	○
Capacitance Stability vs Voltage	○	○	●	●	●	○
Low ESR	●	●	●	●	●	○
Low Inductance	●	●	○	○	●	●
High DC Voltages	●	●	●	●	●	●
High AC Voltages	●	●	●	●	●	○
High AC Current	●	●	●	●	●	○
High Temperature Operation (>125C)	●	●	○	○	●	●
High Frequency Operation (>100kHz)	●	●	●	○	●	○

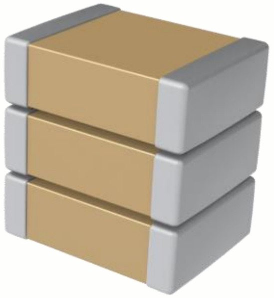
● - Critical Characteristic
○ - Important Characteristic, but not Critical

Capacitor Requirements a Good Match for Class I Ni BME C0G Attributes but capacitance density is a challenge

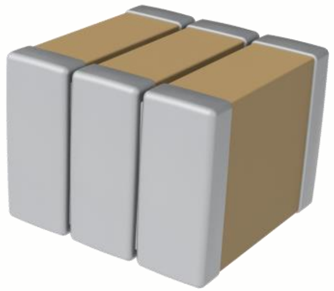
Increasing Capacitance – KONNEKT^{TM} Technology

Two mounting orientations

STANDARD

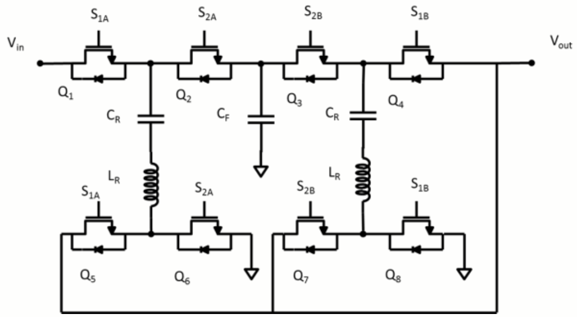


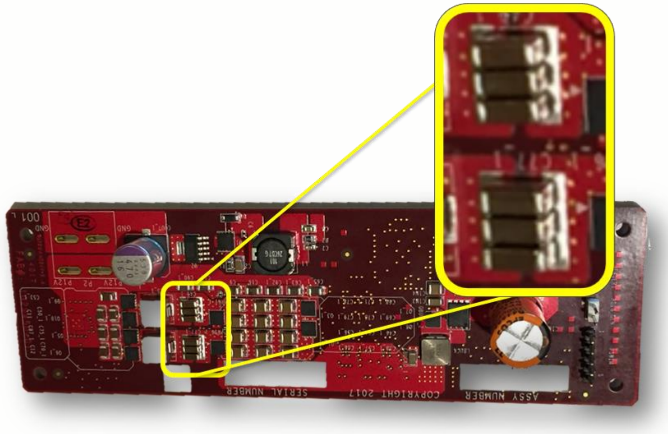
LOW - LOSS

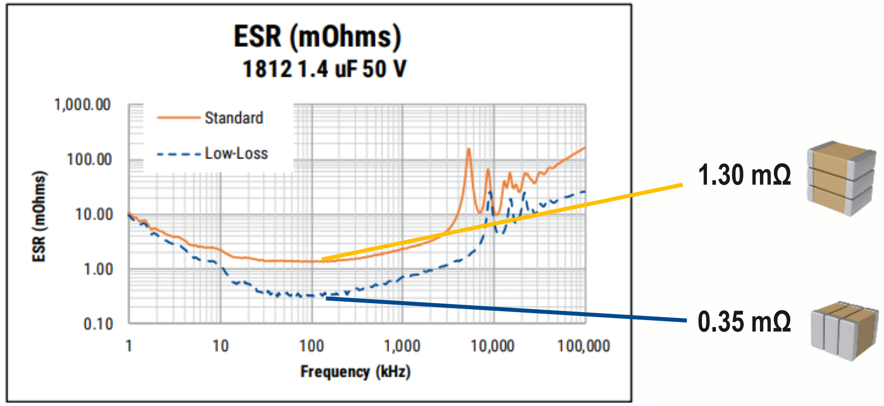


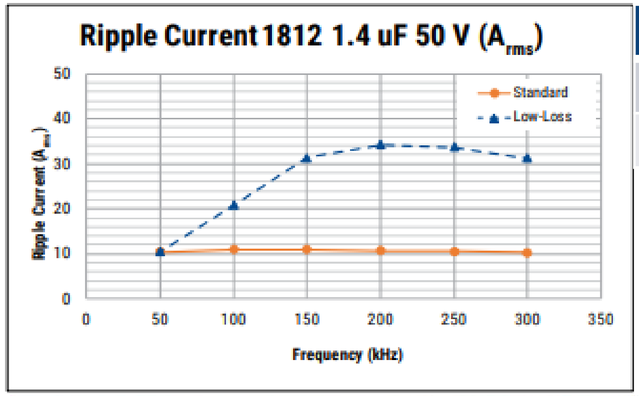
Switched Tank Converter

48V to 12V Power Conversion have 98.92% efficiency In Data Centers





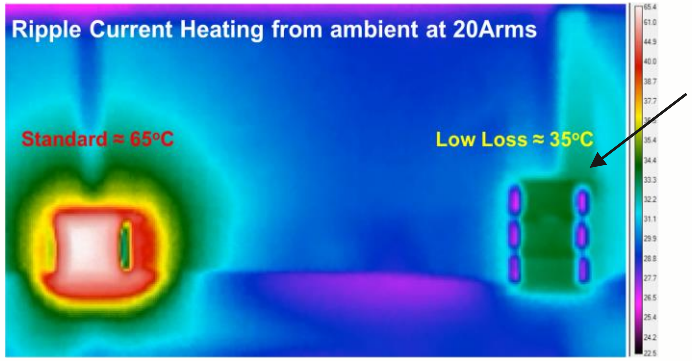




ESL	
Standard	1.6 nH
Low-Loss	0.4 nH

Low-Loss Benefits

- ✓ Lower ESR
- ✓ Lower Thermal Resistance
- ✓ Lower Inductance
- ✓ Higher Ripple Current

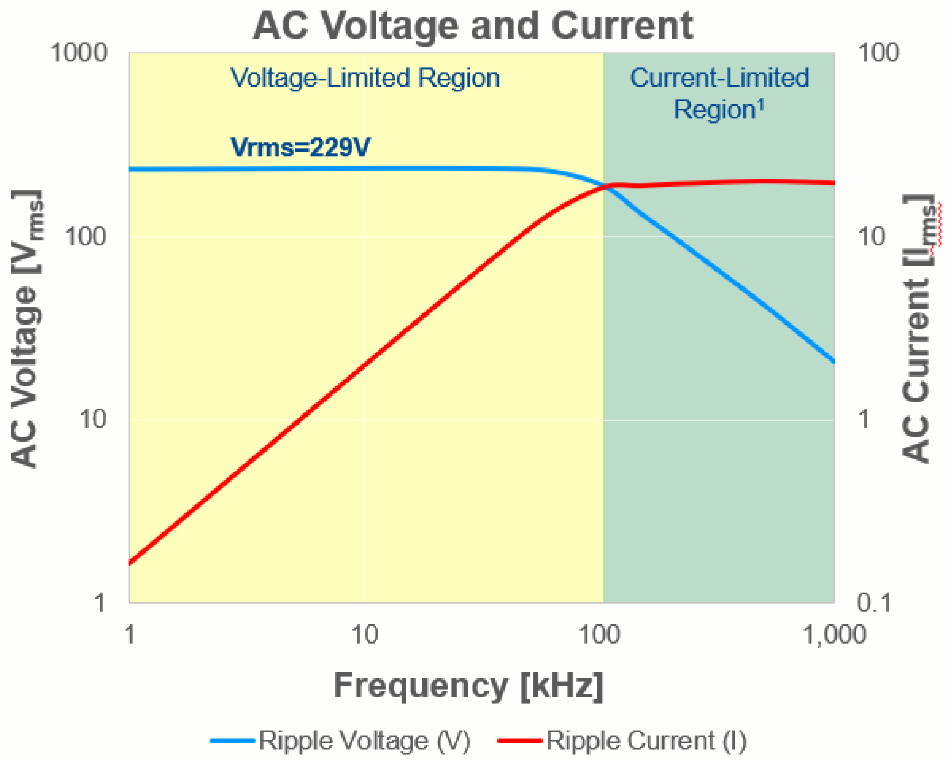


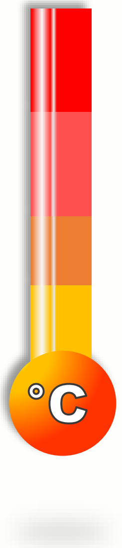
Lower Losses
$P_w = i^2R$

IEEE PEAC'2018
The 2nd IEEE International Power Electronics and Application Conference and Exposition

Development and Characterization of Resonant Capacitors and Inductors for Switched Tank Converters, J. Bultitude & Y. Saito et al

Two Considerations for AC Applications





High AC voltages

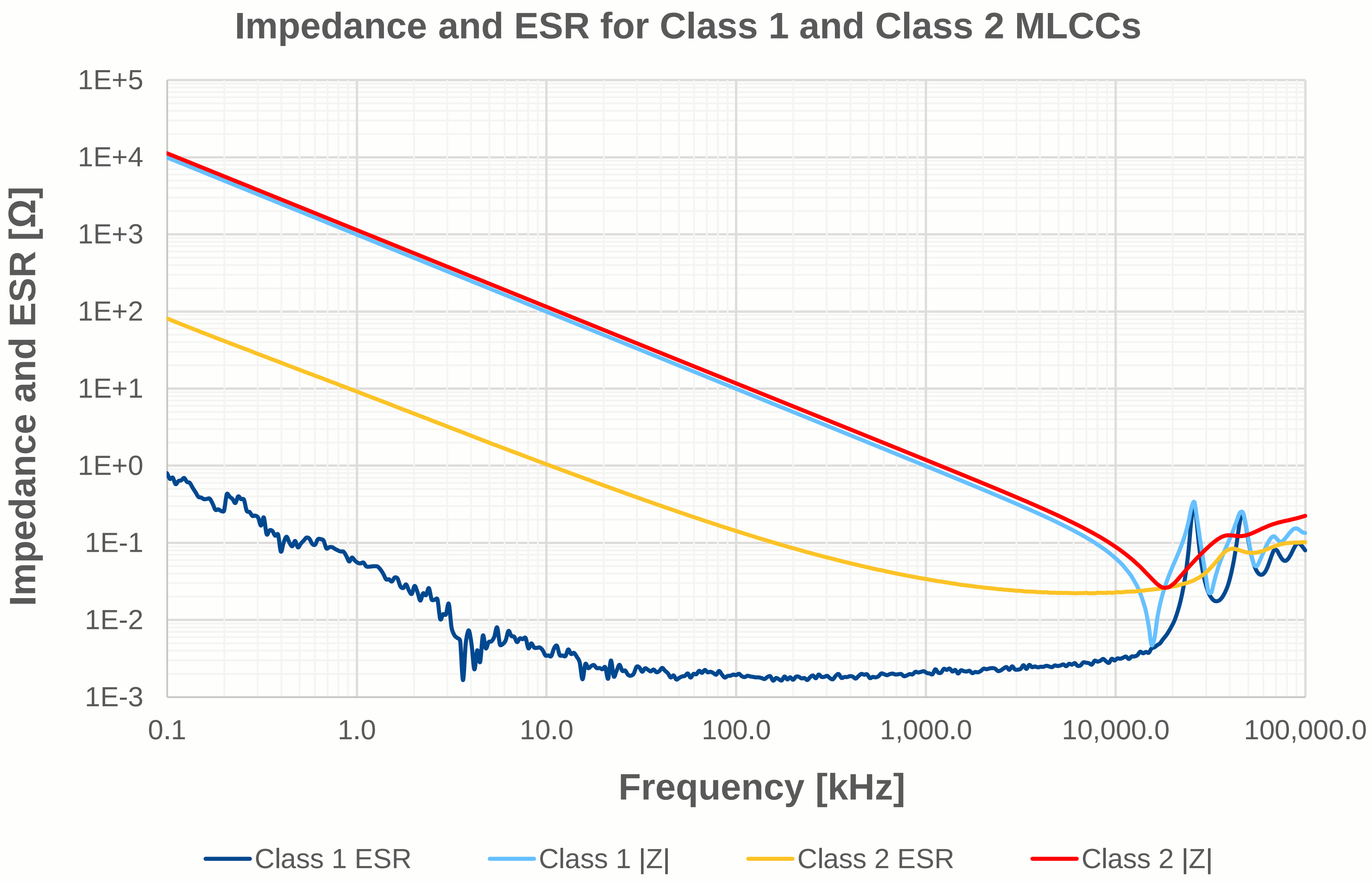
Voltage Limited Region

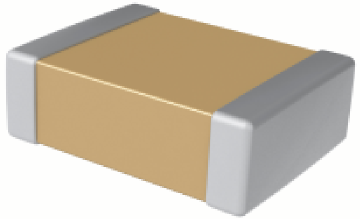
Heating due to I^2R losses

Current-Limited Region

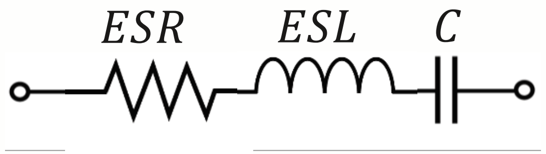
AC Characteristics

Class I and Class II MLCCs





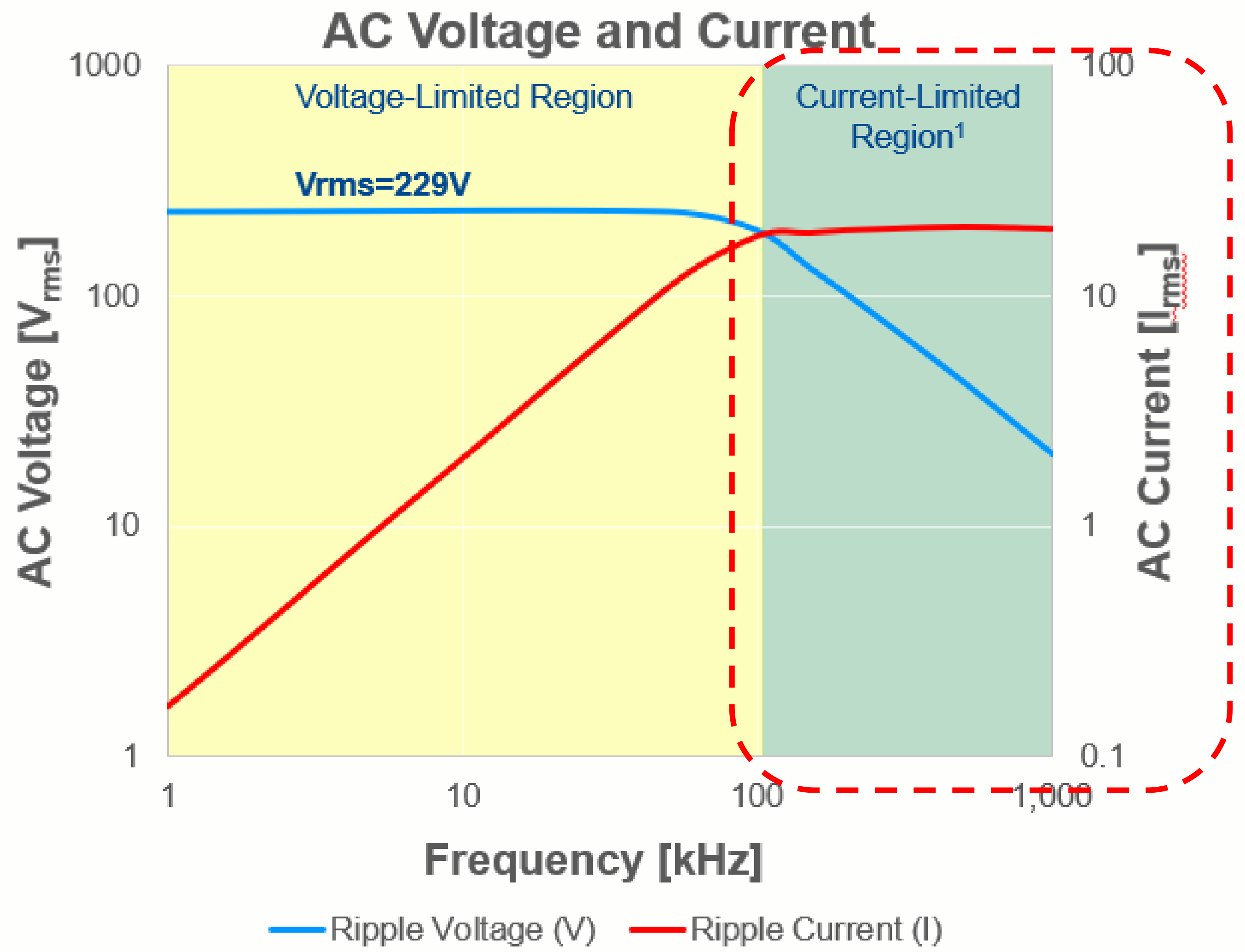
RLC equivalent circuit schematic



$$V_C = I_C \cdot \left[ESR + j\omega ESL - \frac{1}{j\omega C}\right]$$

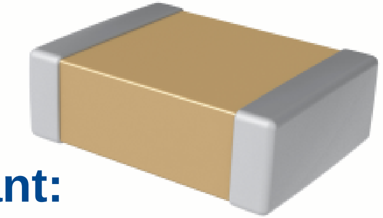
$$I_C = V_C \cdot \frac{1}{\left[ESR + j\omega ESL - \frac{1}{j\omega C}\right]}$$

Heating Due to I^2R Losses
Current-Limited Region



Heating Due to I^2R Losses

Current-Limited Region



$$I_C = V_C \frac{1}{\left[ESR + j\omega ESL - \frac{1}{j\omega C}\right]} \quad \omega = 2 * \pi * f$$

Note: ESL ~ 1nH so negligible effect on
AC current until very high frequencies

If AC Voltage is Held Constant:

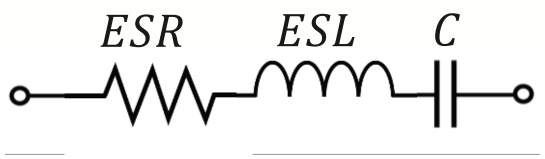
- Higher frequencies result in higher AC currents
- Higher capacitance results in higher AC currents

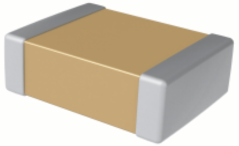
At higher frequencies and capacitance values, even low AC voltages can generate a lot of AC current:

Capacitance	Frequency	AC Voltage	AC Current
15 nF	100 kHz	10 V_{rms}	0.094 A_{rms}
150 nF	1 MHz		9.4 A_{rms}

Heating Due to I^2R Losses

Current-Limited Region





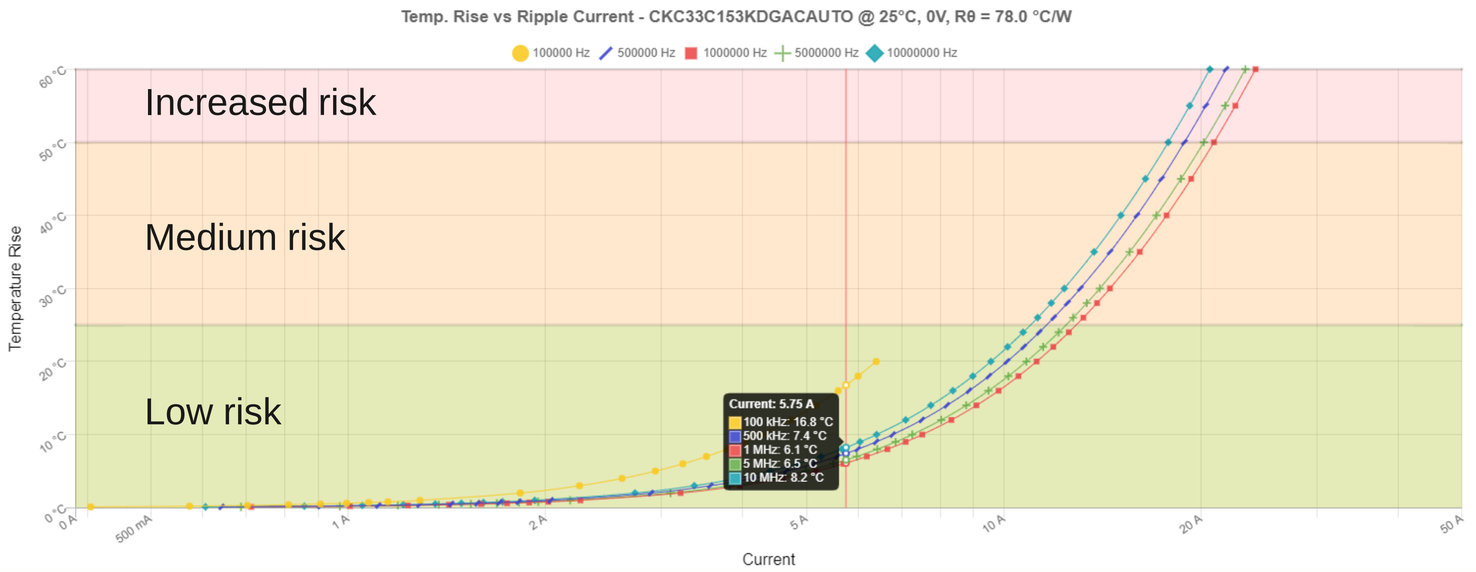
$$P = I^2 ESR$$

$$T_{rise} = P \cdot R_{\theta}$$

where

$R_{\theta} = Thermal\ Resistance\ of\ MLCC$

$P = Dissipated\ Power\ (Heat)$



$ESR = 40mOhms$

$I = 5Arms$

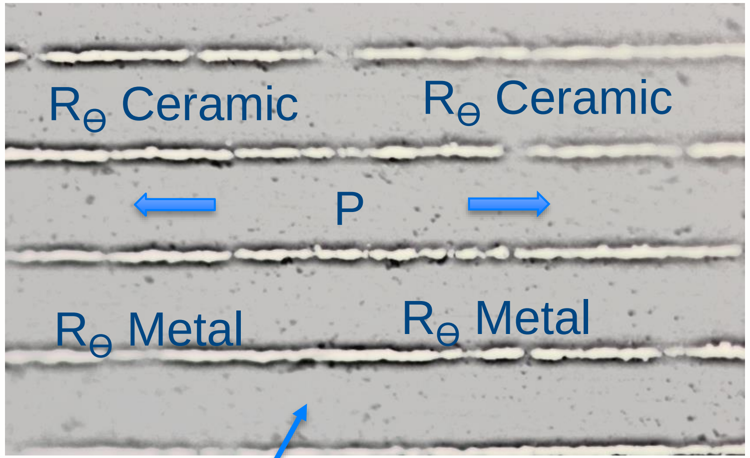
$R_{\theta} = 32^{o}C/W$

$P = 5^2 * 0.04 = 1.01W$

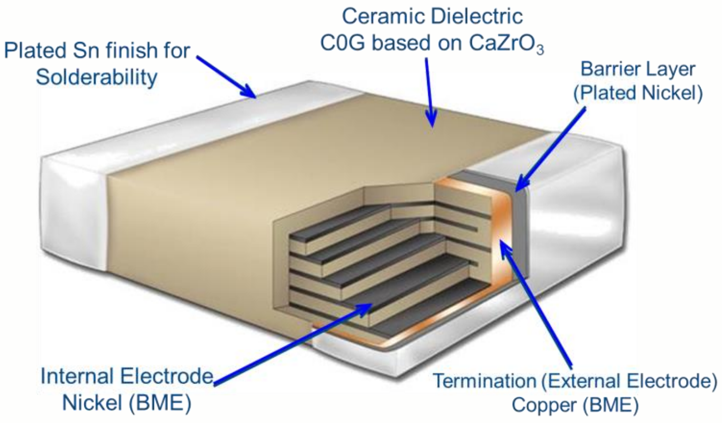
$T\_rise = 10 * 32 = 32^{o}C$

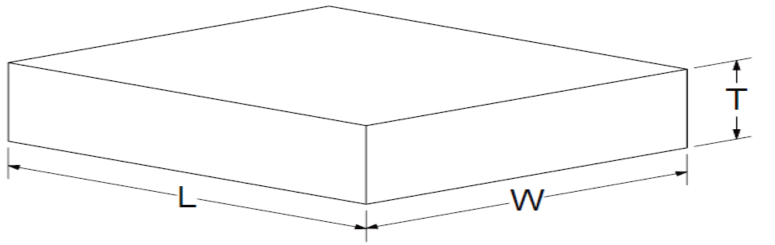
Temperature Zone	Risk
≤ 25˚C above ambient	Low Risk
> 25˚C to ≤ 50˚C above ambient	Medium risk, dependent upon application
> 50˚C above ambient	Increased risk of thermal runaway

Where do we get R_Θ?



Active (parallel plate dielectric layer)





R_Θ = L/(K*A)

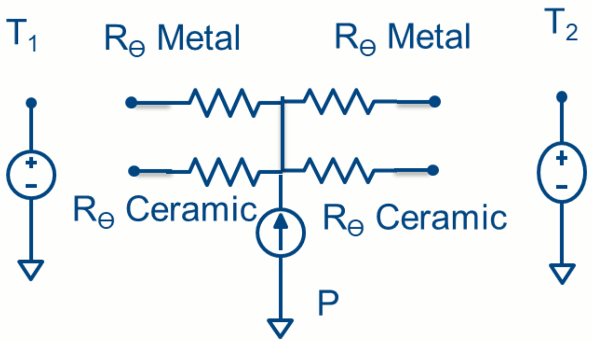
K = thermal conductivity

A = cross sectional area W * T

When L=W

R_Θ per square is 1/(K*T)

P is Dissipated Power (Heat)



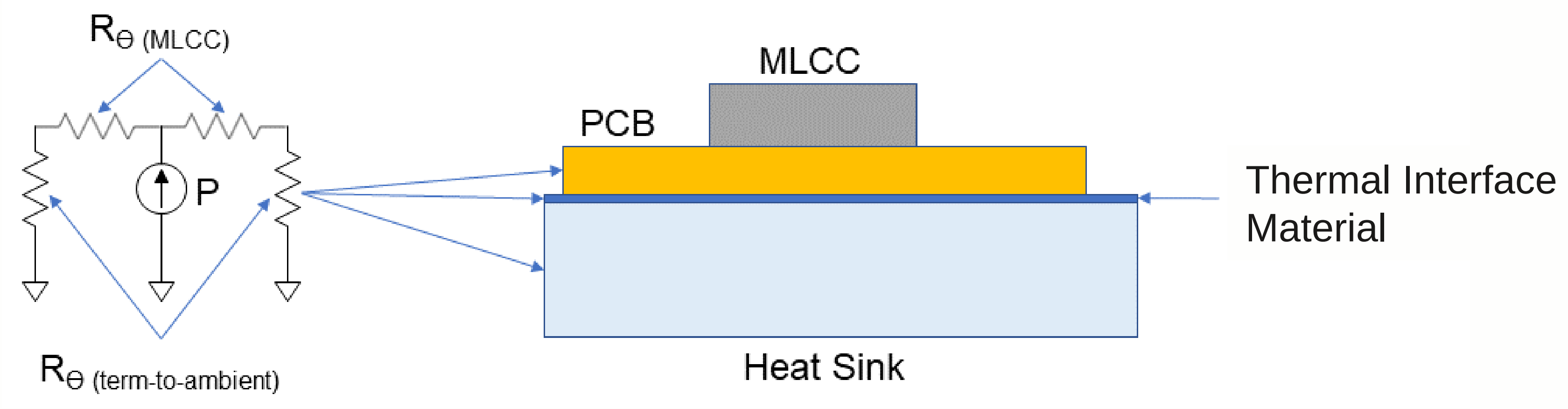
An effective K is calculated for active region from the parallel combination of R_Θ per square of Nickel and $CaZrO_3$ for the number of electrodes and actives in MLCC

	K (W/°C*m)	T (m)	R_Θ per square (°C/W)
Nickel	90	1.2e-6	9.26E+03
$CaZrO_3$	3.0	1.27e-5	2.62E+03

APEC 2019, IS12: ‘Thermal Modeling Challenges for MLCCs in High Power Density Assemblies’ Allen Templeton et al

External Factors Affecting AC Current Performance

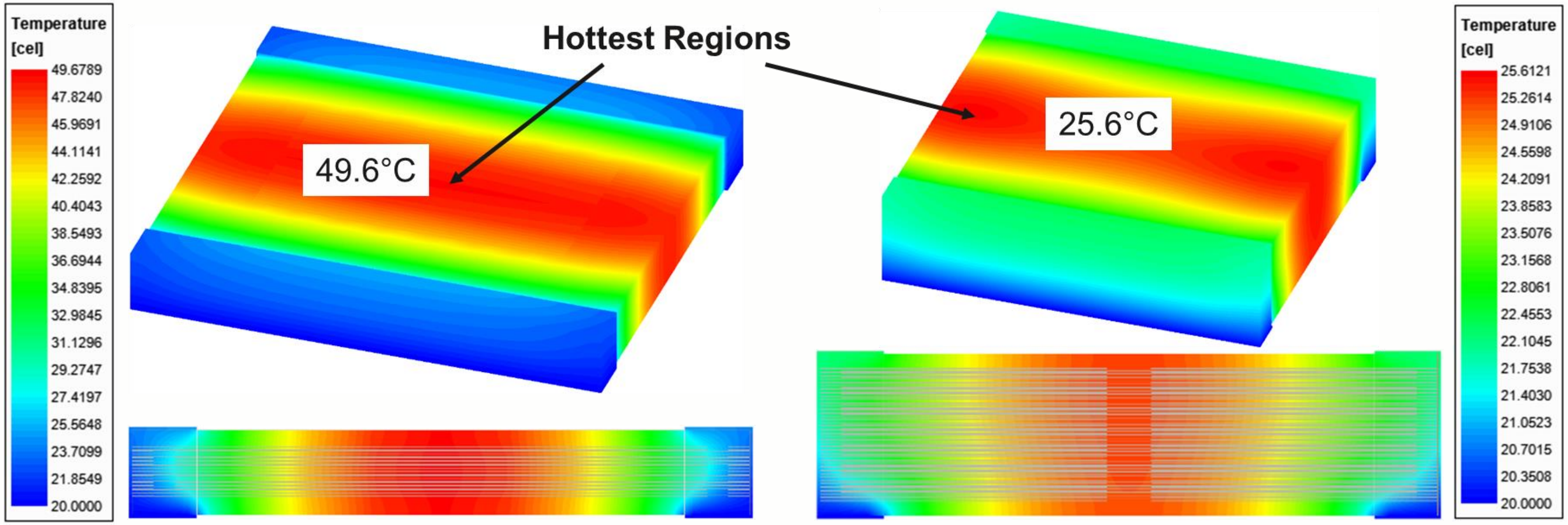
- AC Current depends not only on the I^2R losses, but also:
  - Ambient temperature
  - Thermal characteristics of PCB
  - Active/passive cooling of the MLCC
  - Proximity of the part to other sources of heat (i.e., other capacitors or semiconductors on the same PCB)



Electrothermal Simulations @ 500kHz & 20Arms
Standard Vs 2-Serial

Standard 3640, 33nF, 650V, C0G

2-Serial 3640, 47nF, 1200V, C0G

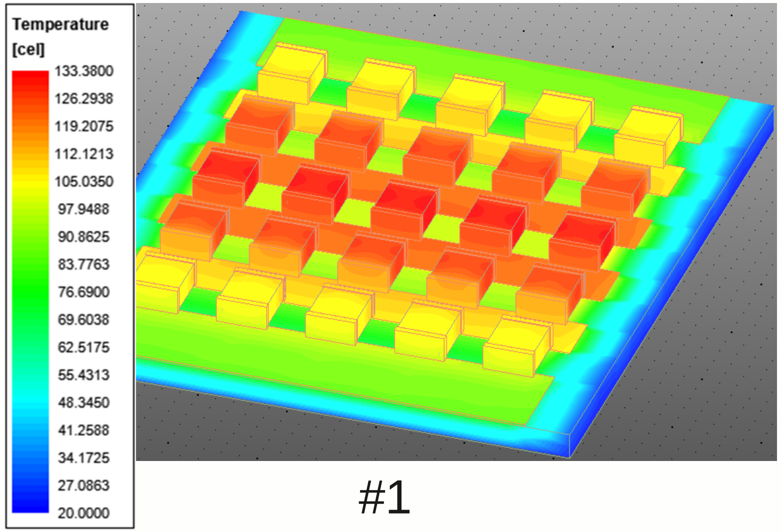


- 2 Serial design with more electrodes dissipates heat better than standard in this example but is a much thicker MLCC

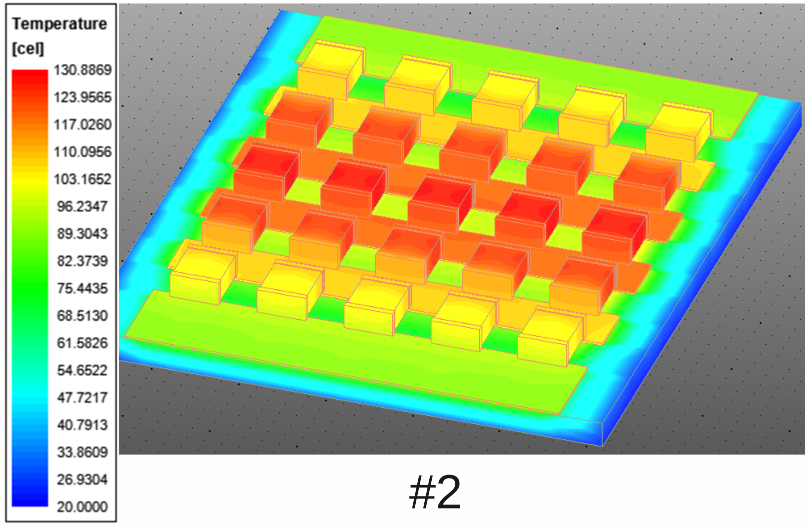
Session T04: 'Steady-State Heat Transfer in Class I MLCCs for Resonant Power Converter Applications' Hunter Hayes

Thermal Simulations of 5x5 Arrays of 1210 MLCCs @ 0.5W/MLCC

PCB Attribute	# 1	# 2	#3
Cu Thickness (oz/ft^2)	2	4	2
PCB Dielectric Thermal Conductivity (W/m-K)	0.35	0.35	2
Max. Array Temperature (^{o}C)	133.4	130.9	50.8



#1



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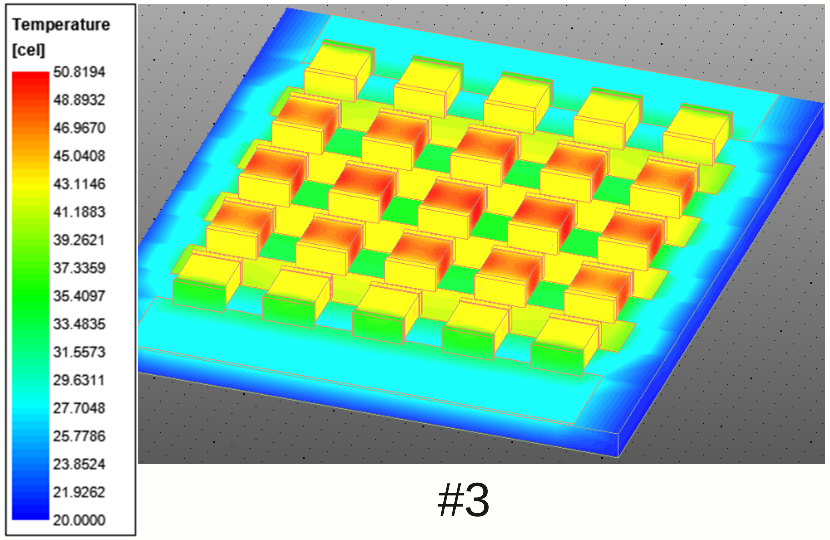
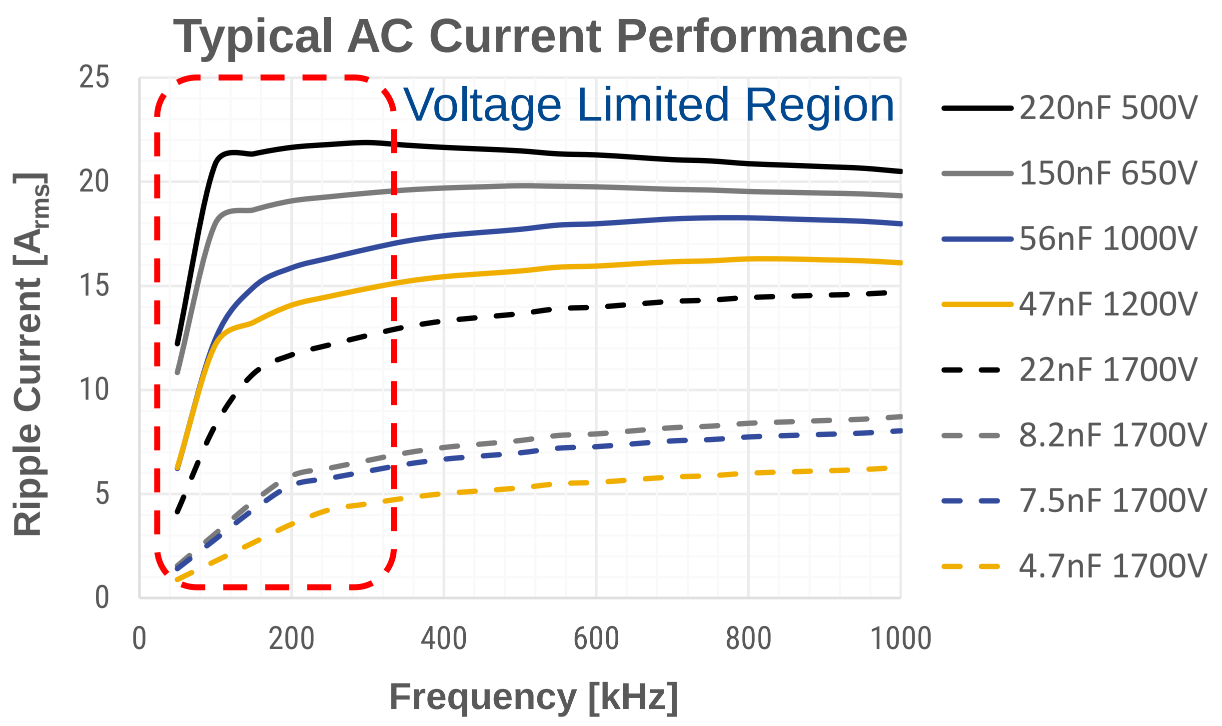


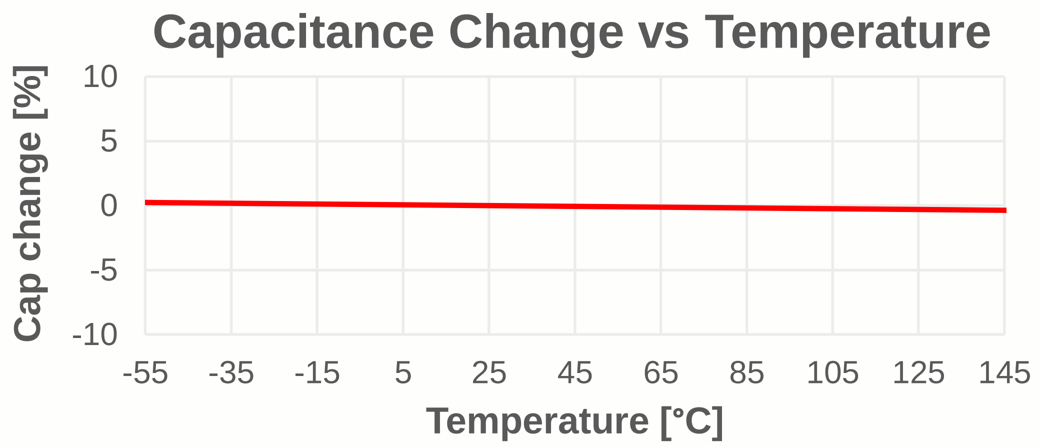
#3

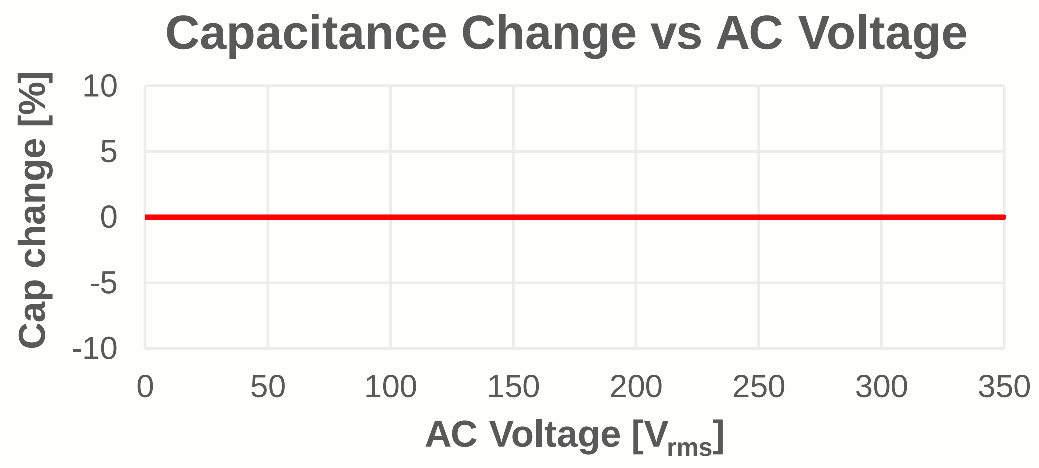
Circuit Board Thickness = 1.5mm; MLCC Separation 2mm

Class I C0G MLCCs for Resonant Applications

- Stable capacitance
- High ripple current performance

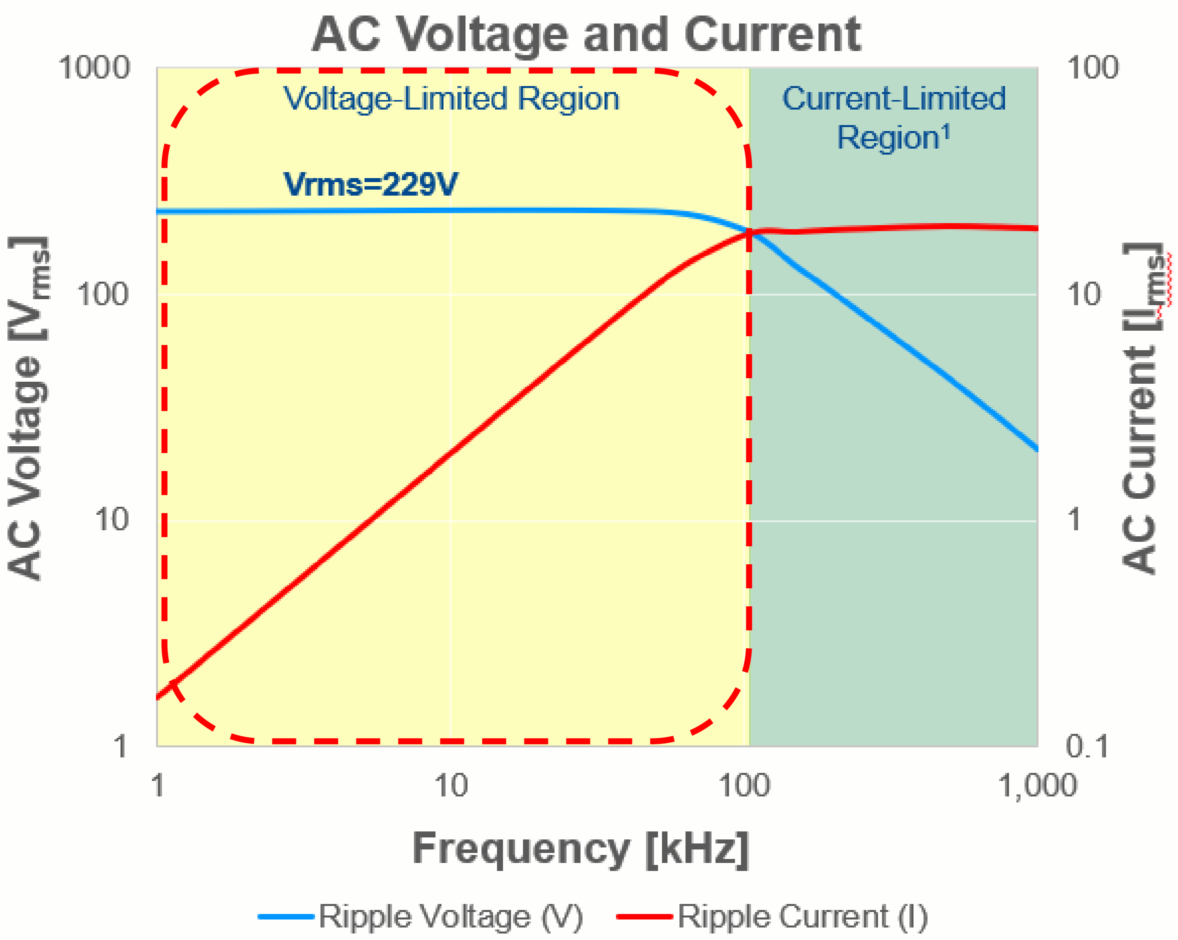






https://content.kemet.com/datasheets/KEM_C1039_KC-LINK_C0G.pdf

High AC Voltages
Voltage-Limited Region



High AC Voltages

Voltage-Limited Region

$$V_C = I_C \cdot \left[ESR + j\omega ESL - \frac{1}{j\omega C} \right]$$

$$\omega = 2 * \pi * f$$

Note: ESL ~ 1nH so negligible effect on
AC current until very high frequencies

If AC Current is Held Constant:

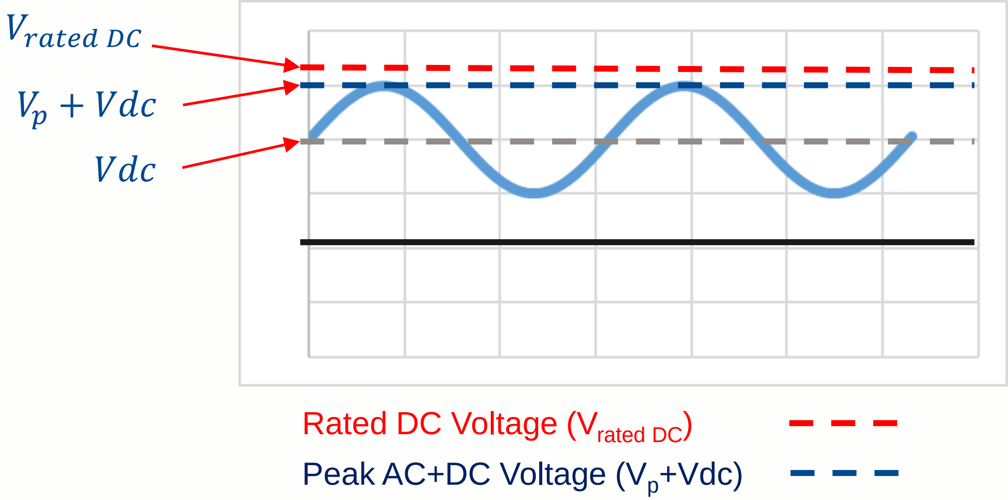
- Lower frequencies result in higher AC voltages
- Lower capacitance results in higher AC voltages

Even if ripple current does not cause excessive heating, peak AC voltage needs to be considered

Two AC Voltage Rules

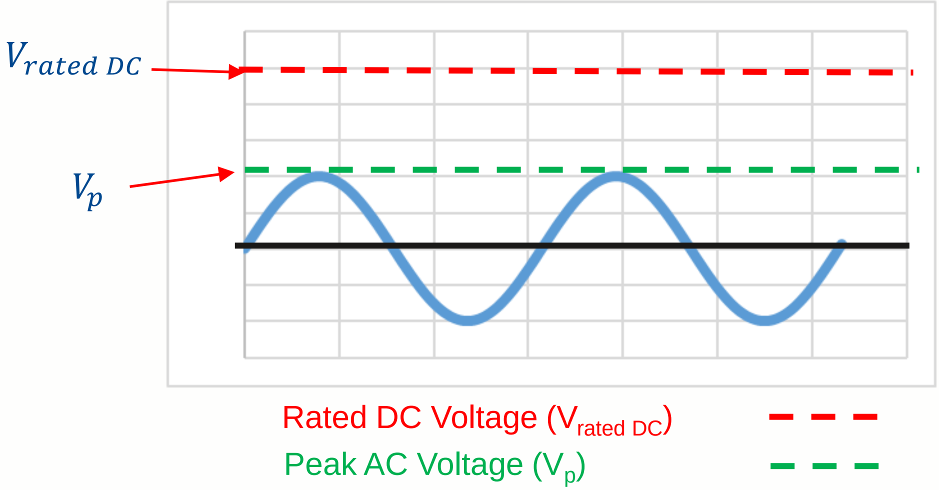
Rule #1:

$$V_p + Vdc < V_{rated\ DC} \qquad V_p = \frac{V_{pp}}{2}$$



Rule #2:

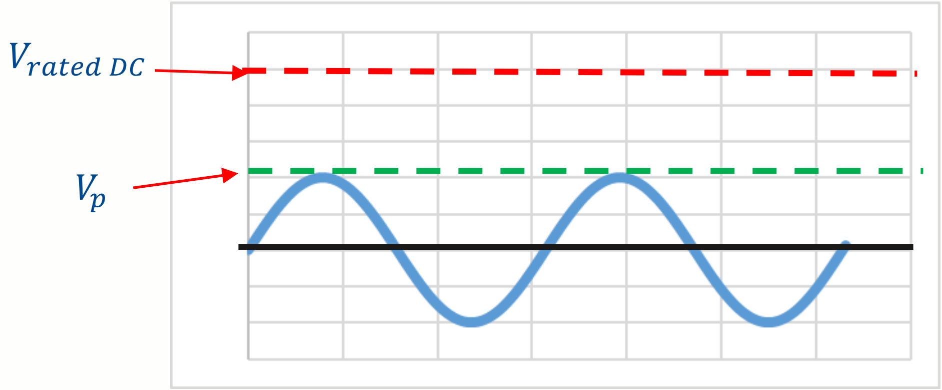
$$V_p < \frac{V_{rated\ DC}}{2} \Rightarrow V_{rms} < \frac{V_{rated\ DC}}{2\sqrt{2}}$$



Two AC Voltage Rules

Rule #2 example:

$$V_p < \frac{V_{rated\ DC}}{2}$$



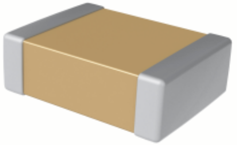
Rated DC Voltage ($V_{rated\ DC}$)

Peak AC Voltage (V_p)

Example:

CKC21C123KEGAC

EIA 2220 / 12nF / 1,200V / Class I C0G



$$V_p = 520V$$

$$520V < \frac{V_{rated\ DC}}{2}$$

$$2V_p = 1,040V < V_{rated\ DC}$$

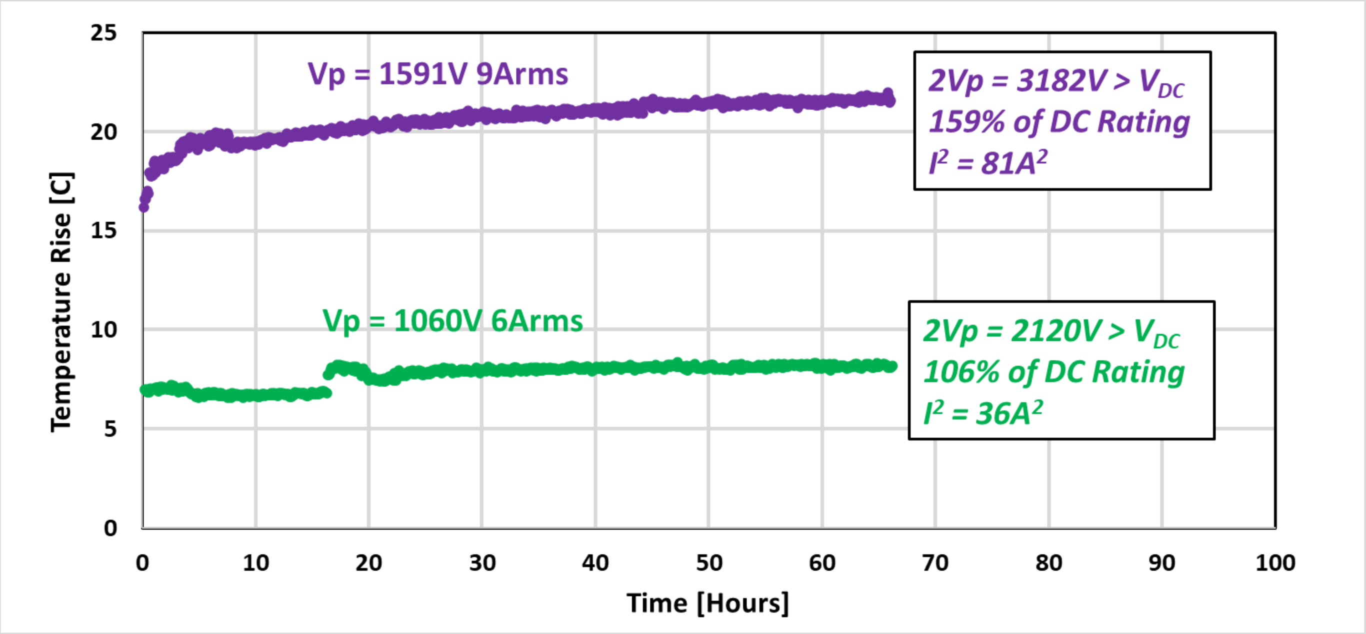
87% of DC Rating

https://content.kemet.com/datasheets/KEM_C1039_KC-LINK_C0G.pdf

New Products – Reduced Heating in Voltage Limited Region

- Voltage Enhanced U2J (VEU2J) MLCCs have been developed with reduced ripple current heating
- *Patents are Pending*
- C3640C153JGJACTU will be released June 2022

3640 15nF 2000V_{DC} Rated VEU2J MLCC
Ripple Current Heating @ 85kHz 25°C



Circuit Board R_Θ = 12 °C/W
No cooling, static air

Summary

- The electrical characteristics of Class I MLCCs make them suitable for many high-power applications
- The performance of these MLCCs in AC voltages depends on their ripple current heating at higher frequencies and voltage capability at lower frequencies but…
- The circuit board design & application environment with respect to heat dissipation must be considered
- Better models of electrothermal performance are giving us better insights into these factors
- New MLCCs are being developed using patent pending technology that can have reduced heating at higher AC voltages

Acknowledgements

- *Thanks to my many collaborators & colleagues at KEMET*

- *ANSYS® for their support of our Electrothermal Model developments*

Any Questions?