Quantifying Allowable AC parameters for DC Rated Ceramic Capacitors

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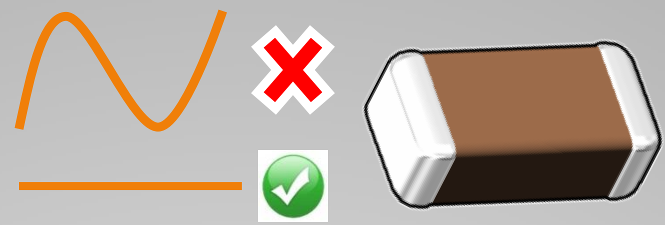
Space constraints of modern AC powered applications have driven the demand for volumetric efficient products.

- noticeable application **Trends** driving the use of high performing DC rated capacitors
- discuss the **Difficulties** of traditional data support for these applications
- provide **Keys** to overcoming the obstacles set forth

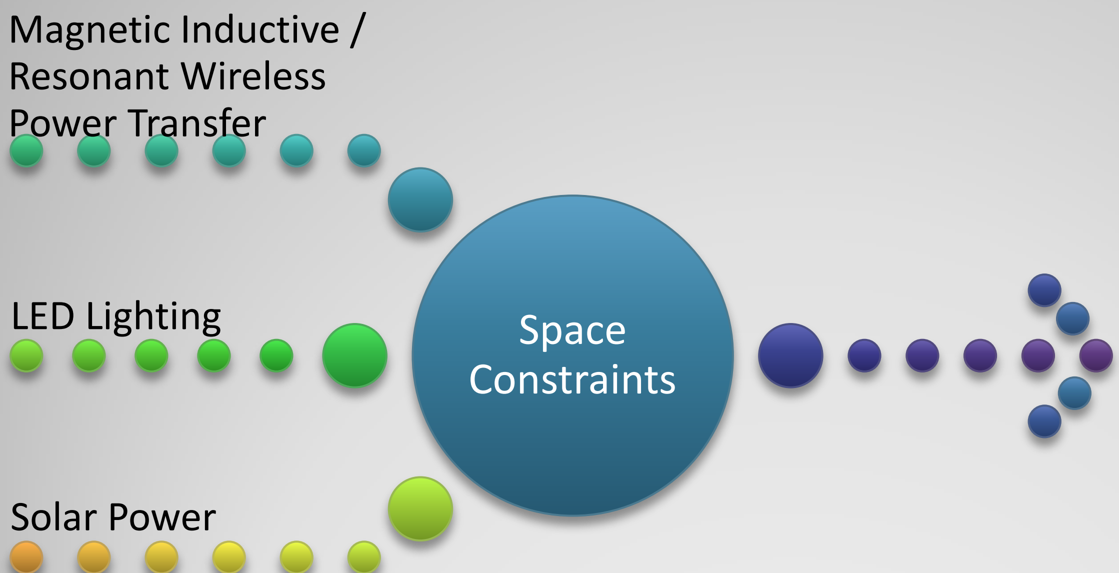
Agenda

Application Trends

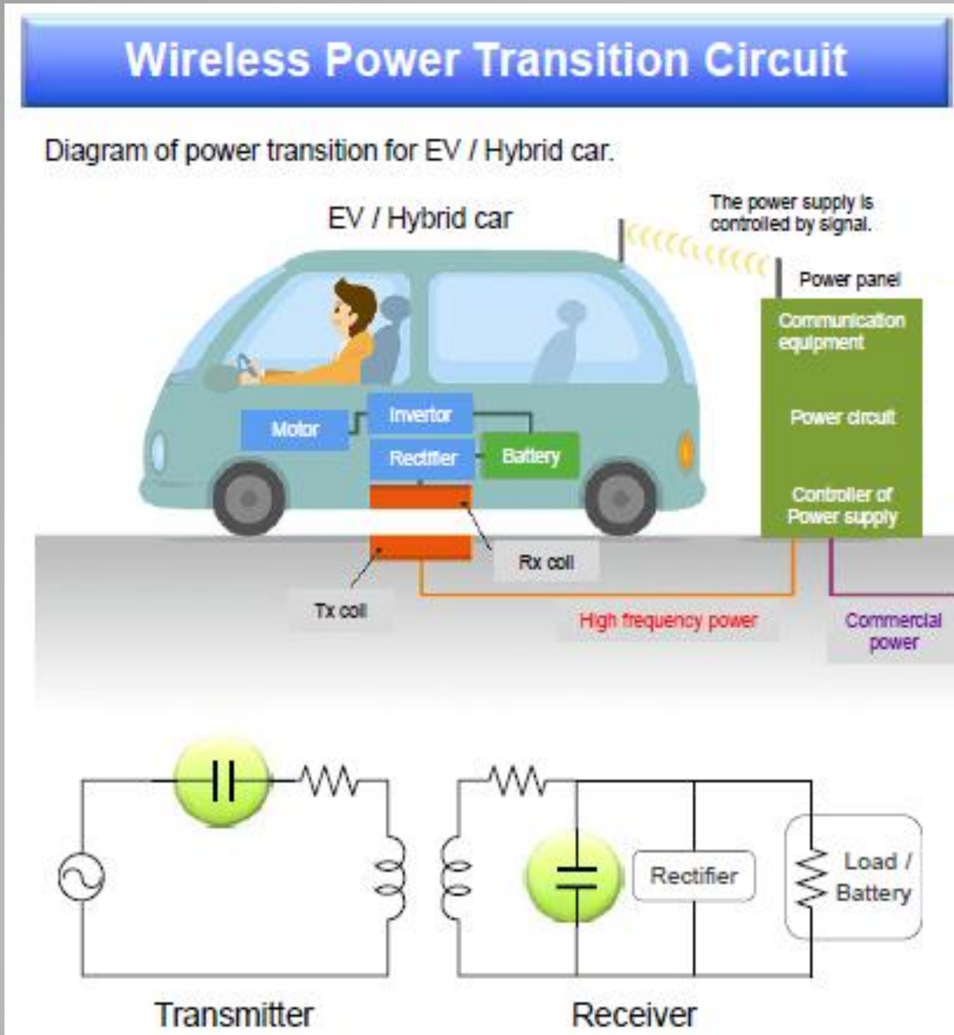
- Traditionally…



- Currently…



Volumetric Efficient Products!!!



Basic LC Resonant Circuit

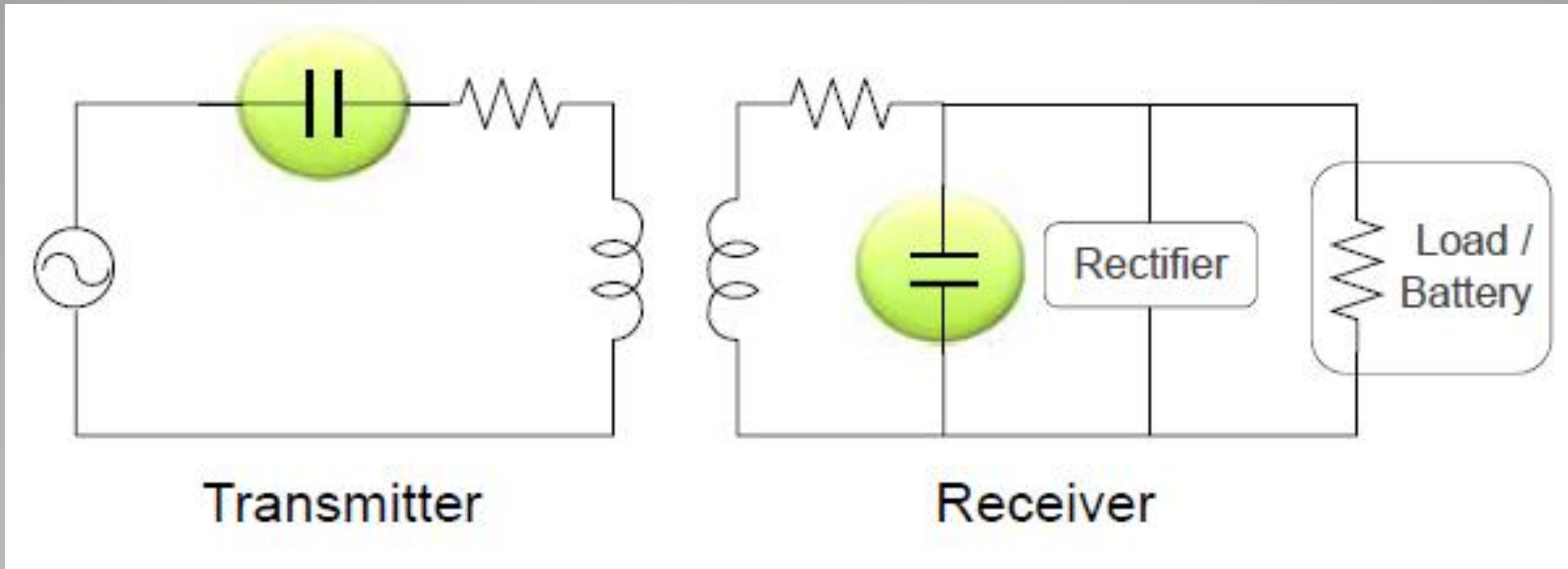
Stringent AC Power Levels

- Voltage is in kV range
- Current is in 10's of Amps range

Key Capacitor Requirements

- Stability with Voltage/Temp
- High Ripple (Low ESR)
- Low Loss (Low D.F.)
- Small Area Consumption
- High Reliability

Technology Comparison

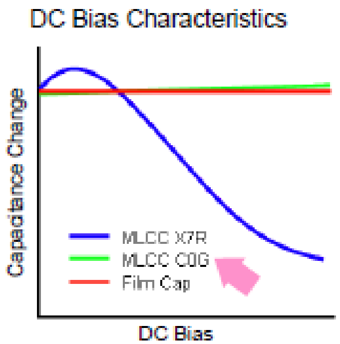


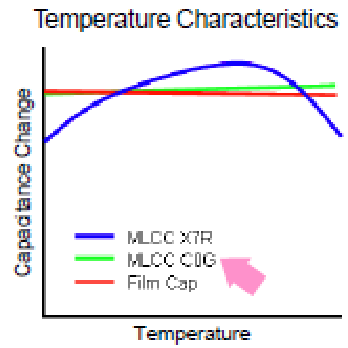
Design optimization is the important element here, but can come at a price. Therefore, MLCC suppliers must work closely with design engineers to verify compliance with end application requirements and ensure proper safety margin is considered while supporting improvement efforts.

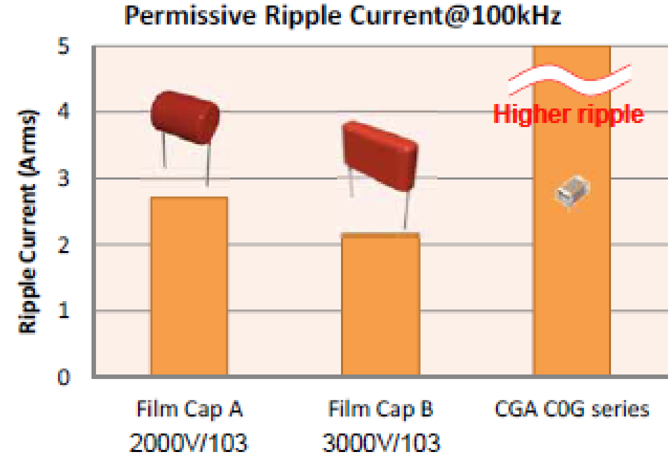
Ex. Use of X7R (Class II dielectric)

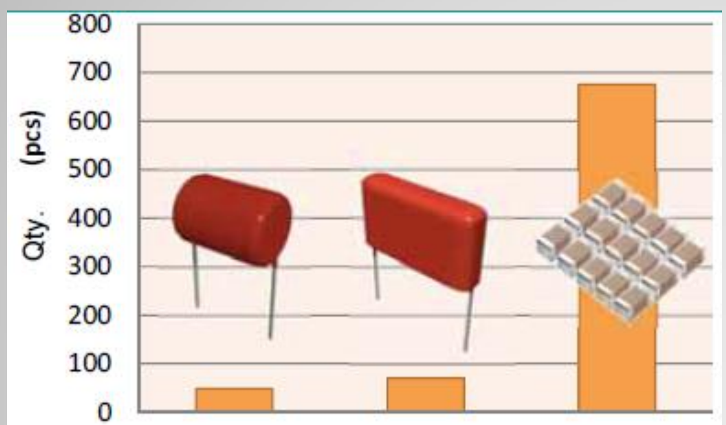
- Provides Cost Savings
- Not Ideal as Series Resonant Capacitor (lack of stability)
- High ESR causes significant efficiency loss in power transition
- Quality Factor is orders of magnitude higher than C0G dielectrics

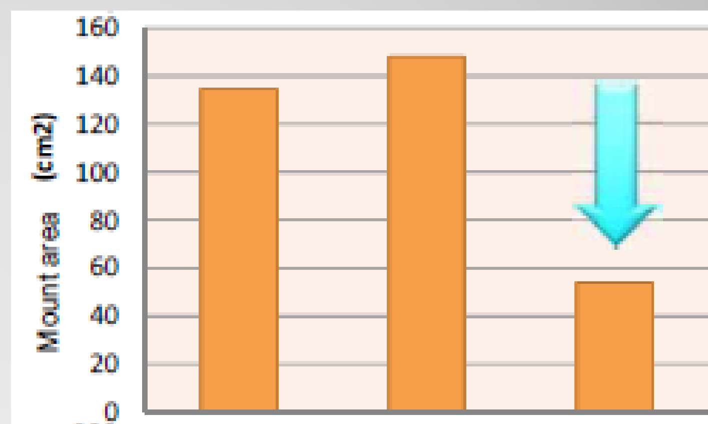
Film capacitors are intriguing because of the high values and stability provided











Ex: Frequency 100kHz
Voltage: 3,000Vrms
Current: 30Arms
Capacitance: 30nF

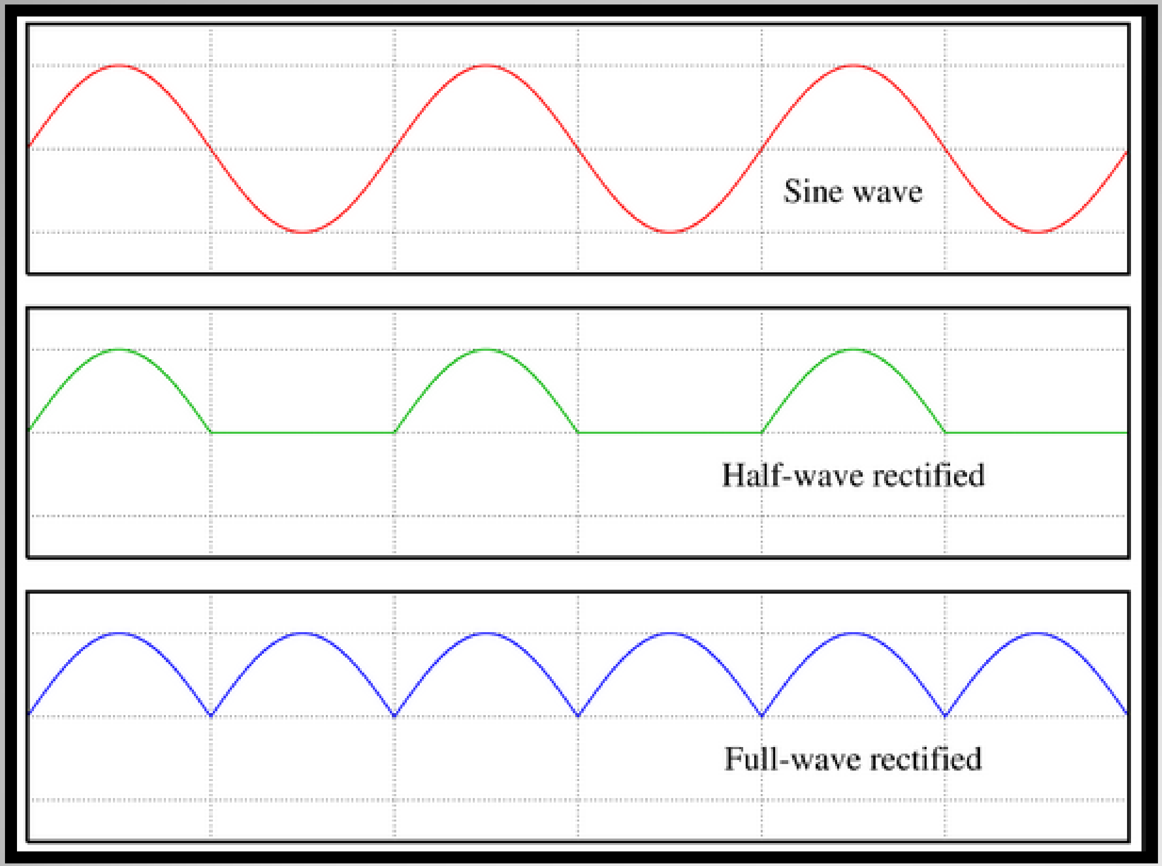
Technology Comparison

- Must define AC Voltage ratings
- Must provide ESR values in lower frequency range for key C0G[NPO] dielectric products
- Must define AC Current ratings
- Must offer ancillary data* to validate use, industry perception, or confusion in AC power applications

*Including reliability concerns

MLCC Supplier Requirements

Rating MLCCs for AC Voltage use has created an unfamiliar position for MLCC suppliers as this product's intended purpose has been DC environments.

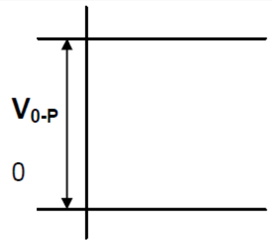
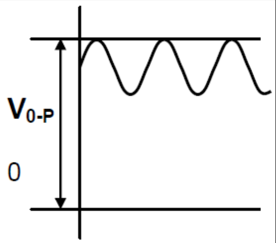
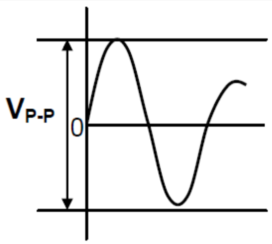


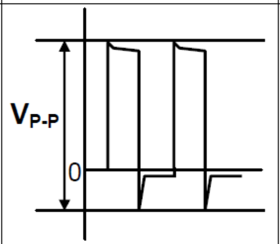
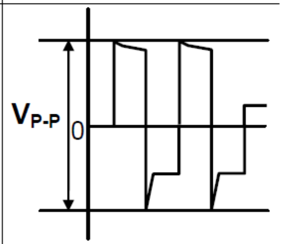
- Measurement Data not readily available
- Testing requires new equipment

AC Voltage Measurement Challenge

AC VOLTAGE RATING

1. Operating voltage across the terminals should be below the rated voltage.
   When AC and DC are super imposed, V0-P must be below the rated voltage.
   Reference: figures 1 and 2 below.
   AC or pulse with overshooting, VP-P must be below the rated voltage.
   Reference figures 3, 4, and 5 below.
   When the voltage is started/ stopped to apply to the circuit an irregular voltage may be generated for a transit period because of resonance or switching. Be sure to use the capacitor within rated voltage during these Irregular voltage periods.

Voltage	(1) DC voltage	(2) DC+AC voltage	(3) AC voltage
Positional Measurement (Rated voltage)			

Voltage	(4) Pulse voltage (A)	(5) Pulse voltage (B)
Positional Measurement (Rated voltage)		

Voltage Cautions from TDK's general specification

$$V_{rms} = \frac{V_{pp}}{2\sqrt{2}}$$

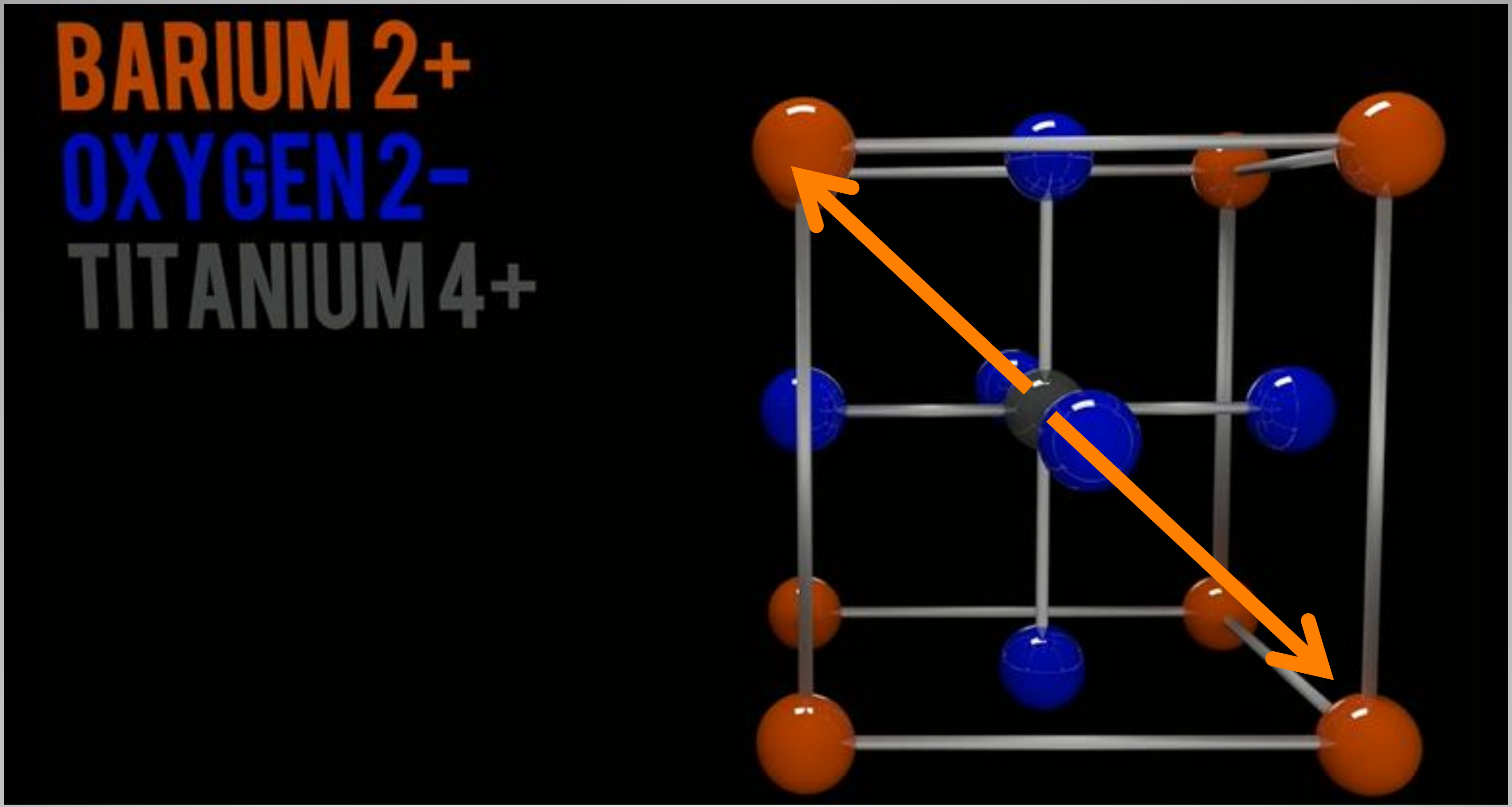
Obtain an AC voltage rating from a DC rated MLCC by substituting the peak to peak voltage (Vpp) for the capacitor's rated voltage and solve for Vrms.

Therefore, a 630Vdc rated MLCC would have the following correlated AC rating:

$$V_{rms} = \frac{630Vpp}{2\sqrt{2}} = 222\text{Vrms}^{1}$$

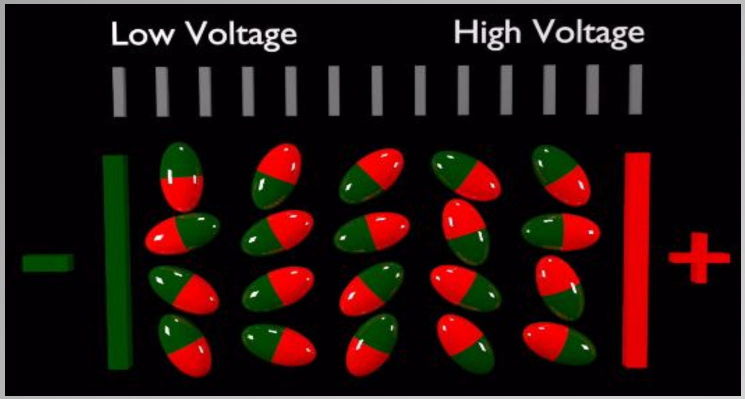
[1]It is worth noting the intention of use is by no means a guarantee for any safety critical AC application where there is potentially a risk of bodily injury.

Maximum allowable rms voltage

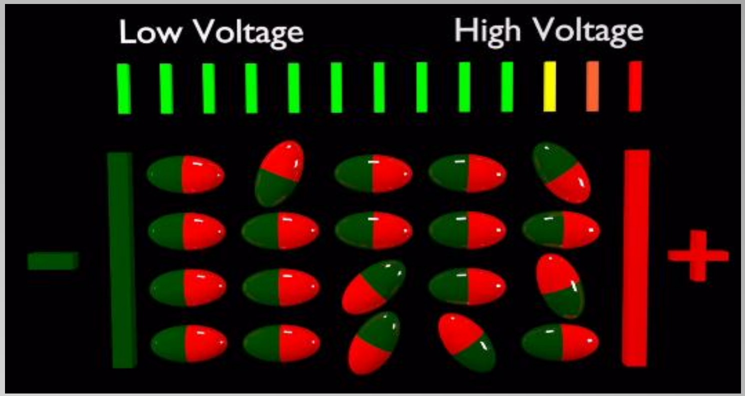


Molecular structure of a Class II dielectric material (Barium Titanate BaTiO3)

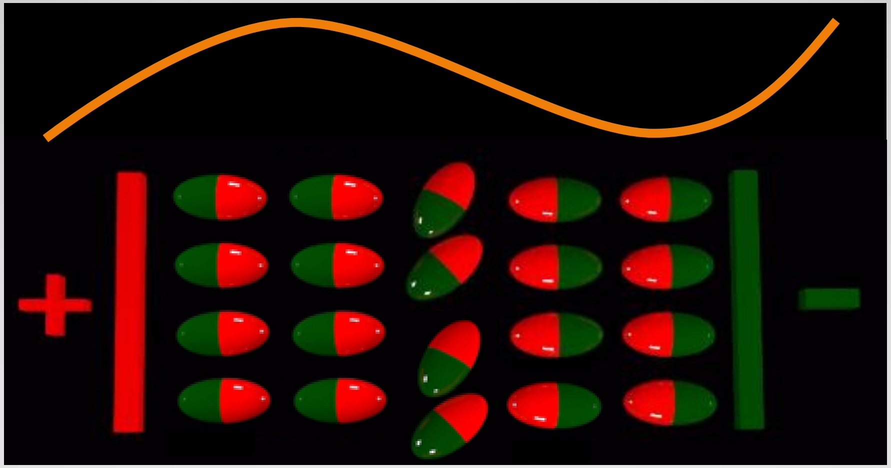
AC Voltage effect on DC Rated Capacitors



Spontaneous Polarization

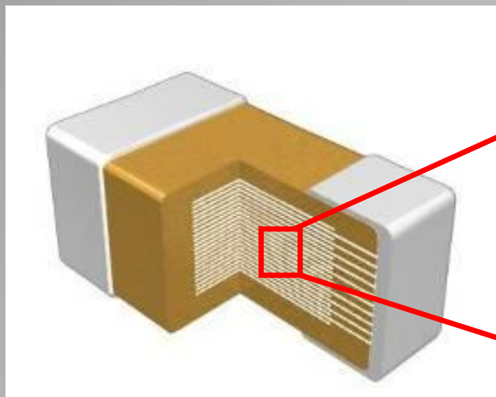


Dipole Alignment to Electric Field

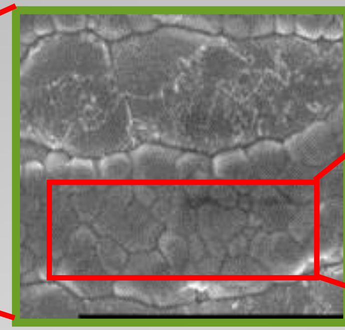


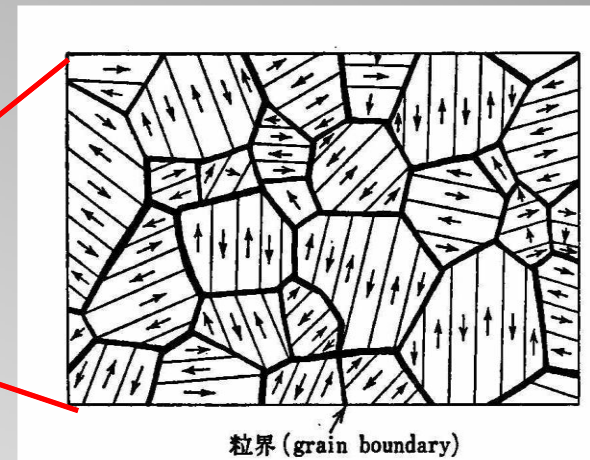
AC Influence: Switching of Polarity

AC Voltage effect on DC Rated Capacitors



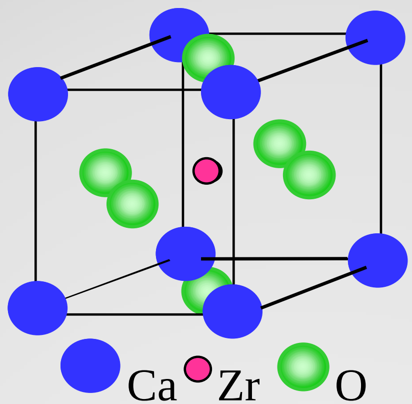
Dielectric enlarged view





Crystal Structure ($CaZrO_3$)

- **Does not have domains**
- **Zr does not shift**
- **Less heating affect**



Bold Black Line: Crystal Grain

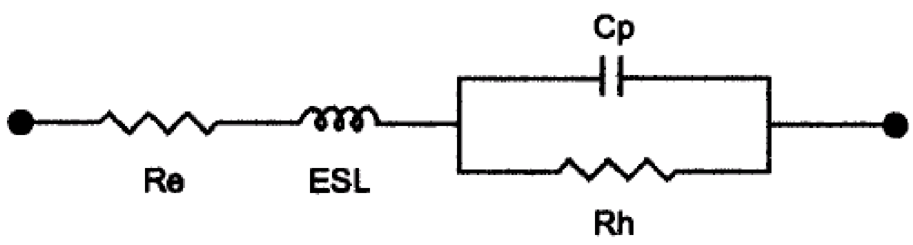
Thin Lines: Domain

Arrows: Dipoles

AC Voltage effect on DC Rated Capacitors

Equivalent Series Resistance (ESR)

ESR is the key parasitic element of all capacitor technologies used for calculating heat generation



Re: Electrode Resistance
Cp: Capacitance
Rh: Hysteresis Derived Resistance, R/f
ESL: Equivalent Series Inductance

ESR = ρ * L/(W * d)

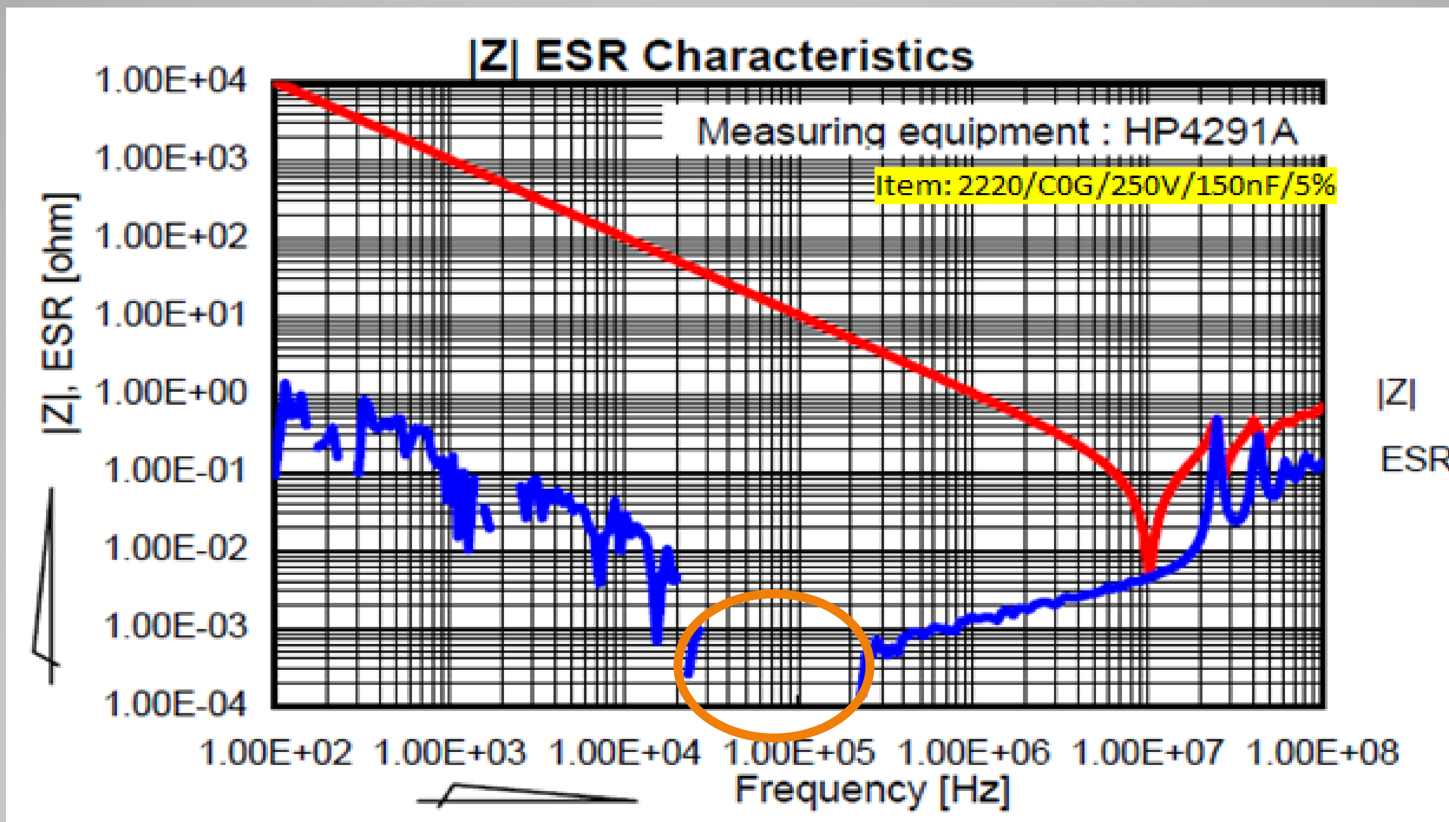
Part 1: Purely electrical resistance. Due to terminal and inner electrodes (metal components)

ρ = resistivity of internal electrode
L = total length of MLCC
W = width of internal electrode
t = thickness of internal electrode
n = number of internal electrode

$$\mathbf{ESR} = (R_{Sn} + R_{Ni} + R_{Cu} + R_{elec)}) + (R_{h)}) + (R_{elec} + R_{Cu} + R_{Ni} + R_{Sn)}) = D.F. \times X_C$$

Part 2: Affected by the dielectric loss of the ferroelectric ceramic material

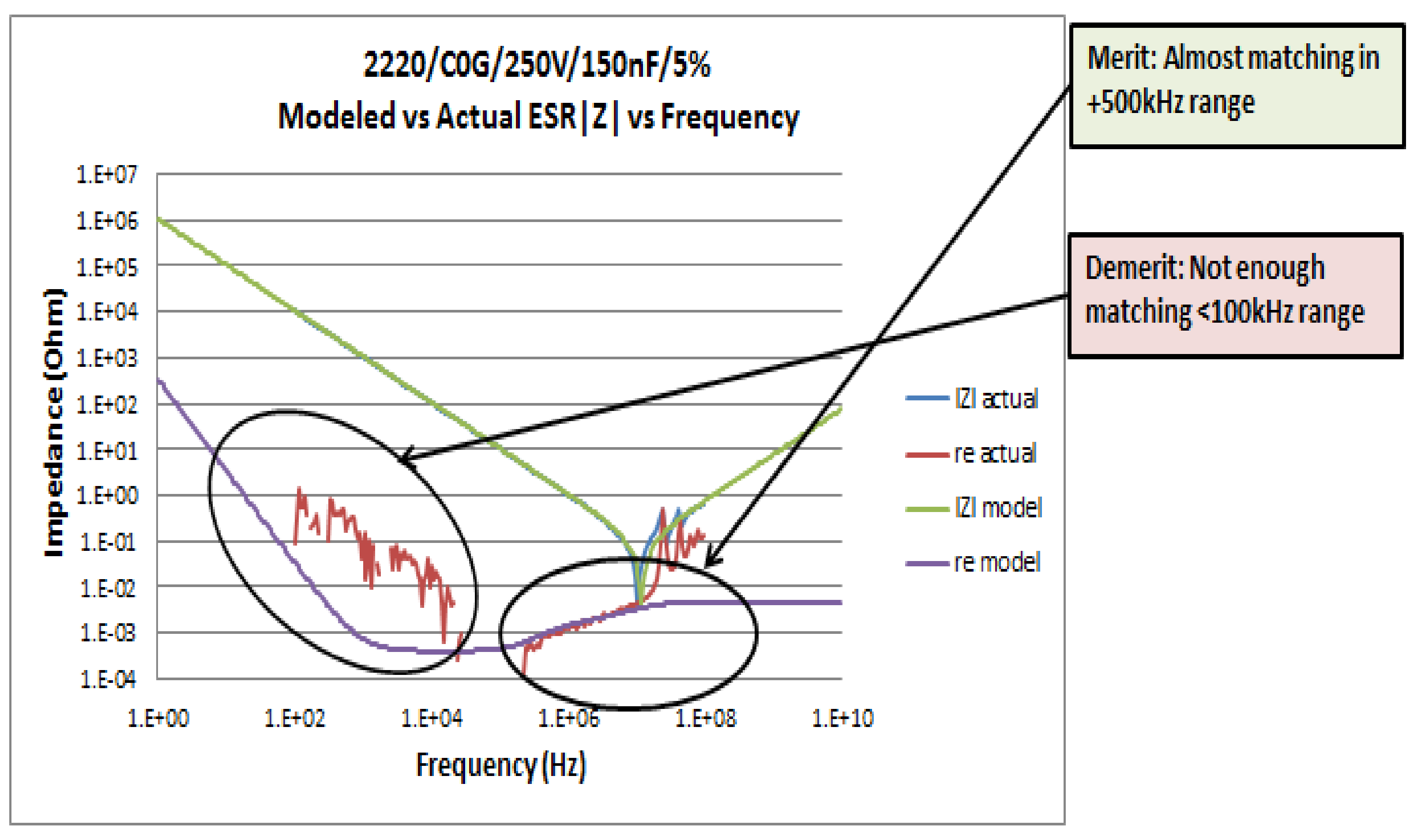
LOW FREQUENCY ESR DATA



Due to inaccuracies in currently available data, measurements of ESR in frequency ranges below 1MHz have been a challenge for all MLCC suppliers.

Typically encountered measurement errors for an EIA case 2220/C0G/250V/150nF/5% MLCC

Due to measurement errors, modeled data is being proposed as an alternate solution



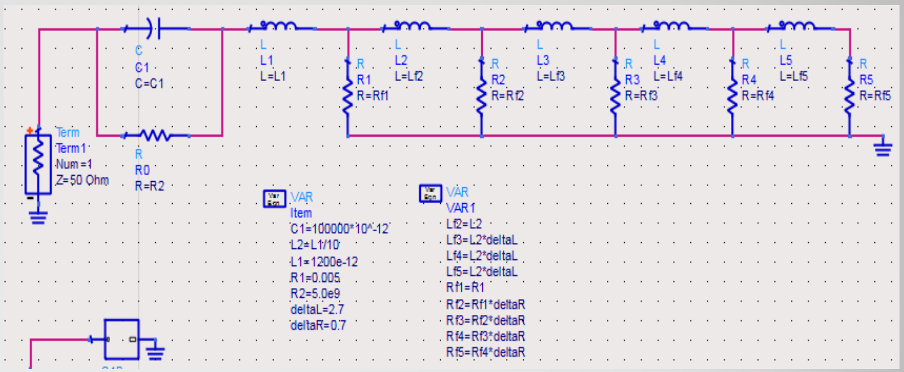
Comparison of Actual and Modeled ESR data

Case Size	Temperature Coefficient	Voltage (V)	Cap Value	ESR at desired measurement frequency									
				60Hz	120Hz	20kHz	50kHz	70kHz	90kHz	100kHz	200kHz	300kHz	400kHz
0402	C0G	50	1nF	14076.20	3521.91	3.94	3.83	3.82	3.82	3.82	3.81	3.82	3.83
0603	C0G	50	1.2nF	11730.97	2935.73	4.09	4.00	3.99	3.99	3.99	3.99	4.00	4.00
0603	C0G	50	1.5nF	9384.19	2348.00	2.68	2.61	2.61	2.60	2.60	2.61	2.62	2.63
0603	C0G	50	1.8nF	7820.33	1956.84	2.41	2.35	2.34	2.34	2.34	2.35	2.36	2.38
0603	C0G	50	2.2nF	6399.48	1602.08	3.00	2.95	2.95	2.95	2.95	2.95	2.96	2.97
0603	C0G	50	2.7nF	5214.51	1305.51	2.56	2.52	2.52	2.51	2.51	2.52	2.53	2.55
0603	C0G	50	3.3nF	4266.18	1067.91	1.86	1.83	1.82	1.82	1.82	1.83	1.85	1.87
0603	C0G	50	3.9nF	3610.47	904.24	2.20	2.17	2.17	2.17	2.17	2.17	2.19	2.20
0603	C0G	50	4.7nF	2996.46	750.87	2.36	2.34	2.34	2.34	2.34	2.35	2.36	2.37
0603	C0G	50	5.6nF	2515.35	630.66	2.45	2.43	2.43	2.43	2.43	2.43	2.44	2.46
0603	C0G	50	6.8nF	2071.03	518.93	1.58	1.56	1.56	1.56	1.56	1.57	1.59	1.61
0603	C0G	50	8.2nF	1718.66	431.55	2.53	2.51	2.51	2.51	2.51	2.52	2.53	2.55
1206	C0G	630	10nF	1408.80	353.37	1.57	1.56	1.56	1.57	1.57	1.59	1.63	1.68
1210	C0G	630	15nF	939.46	235.84	1.31	1.30	1.31	1.31	1.31	1.35	1.42	1.51
1210	C0G	630	22nF	640.69	160.95	1.05	1.04	1.05	1.05	1.06	1.11	1.19	1.30
1206	C0G	250	22nF	640.61	160.87	0.96	0.96	0.96	0.96	0.97	1.00	1.06	1.14
1210	C0G	630	33nF	427.20	107.37	0.77	0.77	0.77	0.78	0.79	0.85	0.96	1.09
1206	C0G	100	33nF	427.30	107.47	0.87	0.87	0.87	0.88	0.88	0.92	0.99	1.07
1812	C0G	630	47nF	300.45	75.89	1.04	1.05	1.05	1.06	1.07	1.15	1.28	1.43
1210	C0G	250	47nF	300.28	75.72	0.87	0.87	0.88	0.88	0.89	0.95	1.04	1.16
2220	C0G	630	68nF	141.42	35.87	0.70	0.70	0.71	0.72	0.72	0.81	0.94	1.09
1812	C0G	450	68nF	207.38	52.17	0.44	0.45	0.47	0.49	0.50	0.66	0.84	1.01
2220	C0G	630	100nF	141.16	35.61	0.44	0.45	0.46	0.47	0.48	0.61	0.76	0.92
1812	C0G	250	100nF	141.16	35.61	0.44	0.45	0.47	0.49	0.50	0.66	0.84	1.01
2220	C0G	250	150nF	94.09	23.73	0.28	0.30	0.31	0.34	0.35	0.50	0.65	0.77
1812	C0G	50	220nF	64.31	16.34	0.35	0.37	0.39	0.41	0.43	0.60	0.78	0.92

*This sheet is calculated by equivalent circuit model for Class I

Unit : mΩ

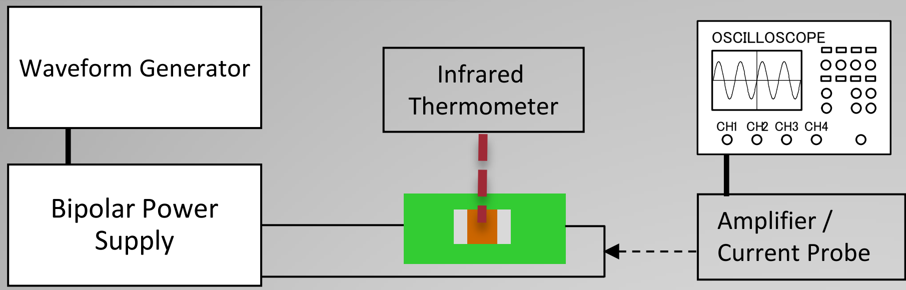
- ECM created using ADS simulation
- Organized in excel to compare simulated and measured data (at higher frequency)



Originally Modeled Data

How to Measure Heat Generation

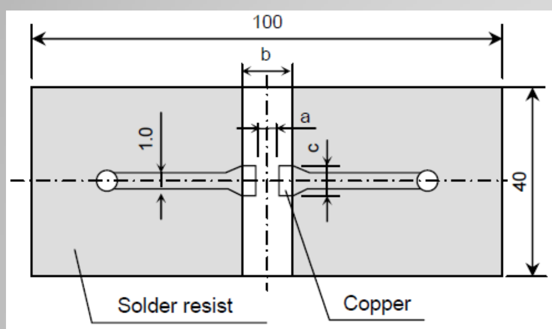
Setting



Equipment:

- Waveform Generator : HP 3312A
- Bipolar Power Supply : NF 4025
- Oscilloscope : HP infinium 54845A
- Infrared Thermometer : TASCO THI-301
- Current Probe/Amplifier : Tektronix A6032/AM503B

Test Board



	TDK Land Pattern		
Chip Size	a	b	c
C1005	0.40	1.50	0.50
C1608	1.00	3.00	1.20
C2012	1.20	4.00	1.65
C3216	2.20	5.00	2.00
C3225	2.20	5.00	2.90
C4532	3.50	7.00	3.70
C5750	4.50	8.00	5.60
C7563	5.50	9.10	6.90

Initial Challenge: limited measurement due to lack of equipment investment

- **AC CURRENT RATING**

$$I_{rms} = \sqrt{\frac{\Delta T}{K \times ESR}}$$

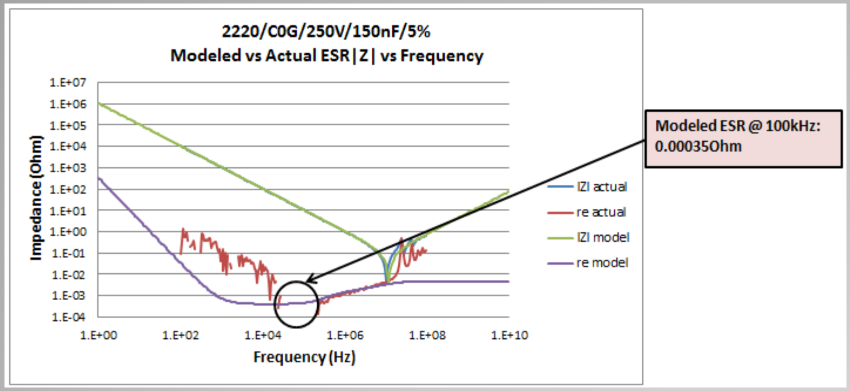
For proper calculation of the AC current rating, one must know several parameters.

Considerations for Delta T

Thermal Resistance (K or R_{th})

Series	K (°C/W)
CKG57K/N (2220+)	460
CKG45K/N (1812+)	488
5750 (2220)	240
4532 (1812)	340
3225 (1210)	370
3216 (1206)	380
2012 (0805)	470
1608 (0603)	740
1005 (0402)	800
0603 (0201)	800
0402 (01005)	800

- May not be publicly released
- Can vary product to product, supplier to supplier, material to material
- TDK provides in its SEAT design tool when simulating for ripple current
- 240 °C/W is used to represent the 2220 package



ESR is typically readily available through design tools. However, one may need to obtain ESR curves from the supplier.

Referencing the same 2220/C0G/250V/150nF/5% capacitor and an operating frequency of 100kHz, the ESR was modeled to approximately 0.35mOhm.

$$I_{rms} = \sqrt{\frac{\Delta T}{K \times ESR}}$$

$$I_{rms} = \sqrt{\frac{20^{o}C}{240^{o}C/W \times 0.00035Ohm}} = 15.46A_{rms}$$

Maximum allowable rms ripple current

TDK Multilayer Ceramic Capacitor (Estimated Failure Rate FIT)

TDK PN	T.C.	R.V.	Test Temp (°C)	Test Voltage (Vdc)	Test Time (hrs)	Qty.	Component Hrs. Tested (Hrs)	Est. Operating Temp (°C)	Est. Operating Voltage (Vdc)	Failure Rate	MTBF (years)	15 year Lifetime Probability
2220/C0G/250V/150nF/5%	C0G	250	125	300	1000	77	77,000	105	200	882.15	1.29E+02	89%
								125	200	3528.62	3.24E+01	63%
								145	200	14114.48	8.09E+00	16%
1812/C0G/250V/100nF/5%	C0G	250	125	300	1000	77	77,000	105	200	882.15	1.29E+02	89%
								125	200	3528.62	3.24E+01	63%
								145	200	14114.48	8.09E+00	16%
1210/C0G/250V/47nF/5%	C0G	250	125	375	1000	77	77,000	105	200	451.66	2.53E+02	94%
								125	200	1806.65	6.32E+01	79%
								145	200	7226.61	1.58E+01	39%
1206/C0G/250V/22nF/5%	C0G	250	125	375	1000	77	77,000	105	200	451.66	2.53E+02	94%
								125	200	1806.65	6.32E+01	79%
								145	200	7226.61	1.58E+01	39%
0805/C0G/250V/10nF/5%	C0G	250	125	375	1000	77	77,000	105	200	451.66	2.53E+02	94%
								125	200	1806.65	6.32E+01	79%
								145	200	7226.61	1.58E+01	39%

Exceeding operating temperature is not recommended or warranted

As temperature increases by 20 °C, the FIT is also increasing at a rate of 4 x while the MTBF is reducing by 4 x

Calculations of failure rate with 60% confidence level

1. Voltage Acceleration Coefficient (Av)

$$A_v = \left(\frac{V}{Vo}\right)^3$$

V : Test voltage
Vo : Estmated operating voltage

Calculated per the JIS C5003 standard

2. Temperature Acceleration Coefficient (At)

$$At = 2^{\frac{T - To}{10}}$$

T : Testing temperature
To : Estimated operating temperature

Lifetime Probability
R(t) = e^(-t/MTBF)

3. Failure Rate (λ)

$$\lambda = \frac{r}{\Sigma t} \times k$$

r : Number of failure
Σ t : Total testing time
k : Constant which is changed by r
If r = 0, then k is 0.917

4. Failure Rate with acceleration (λo)

$$\lambda o = \frac{\lambda}{Av \times At} \quad \text{(FIT)}$$

1 FIT = 1 x 10^{-9}

5. MTBF (Mean Time Between Failure)
MTBF = 1 / FR

Disclaimer: *Calculations provided are estimates of product life based on details above, actual performance may vary. TDK does not guarantee the life of its MLCCs.*
The predicted failure rates in failure per billion device-hours (FIT)

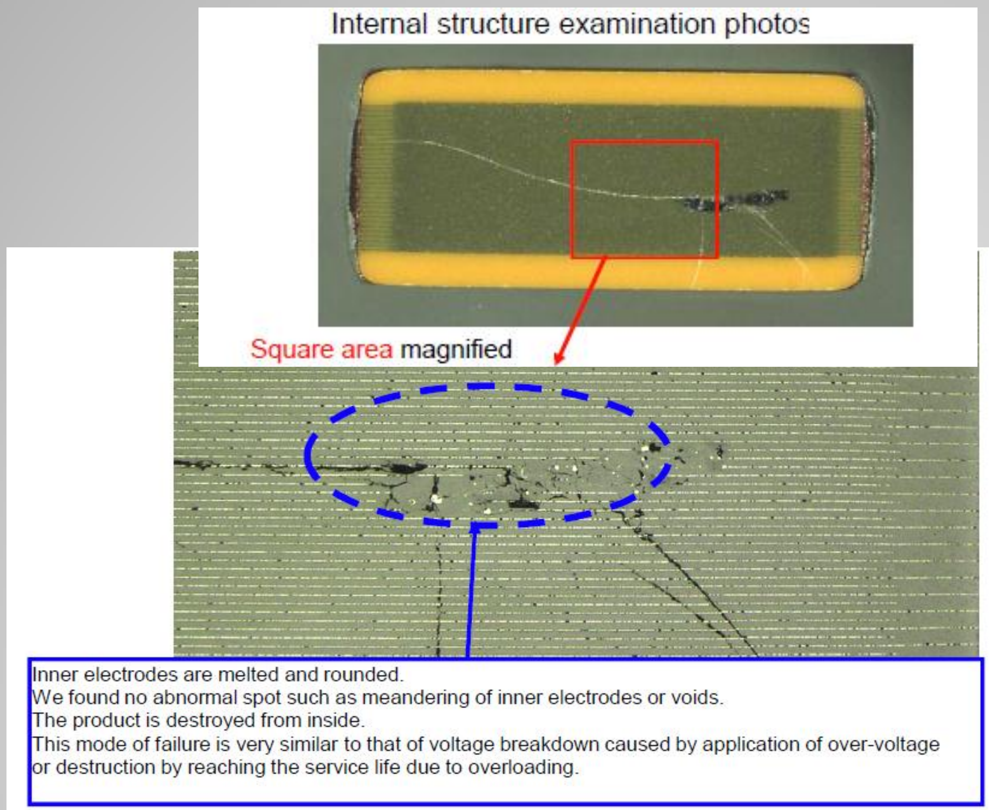
RELIABILITY CONCERNS

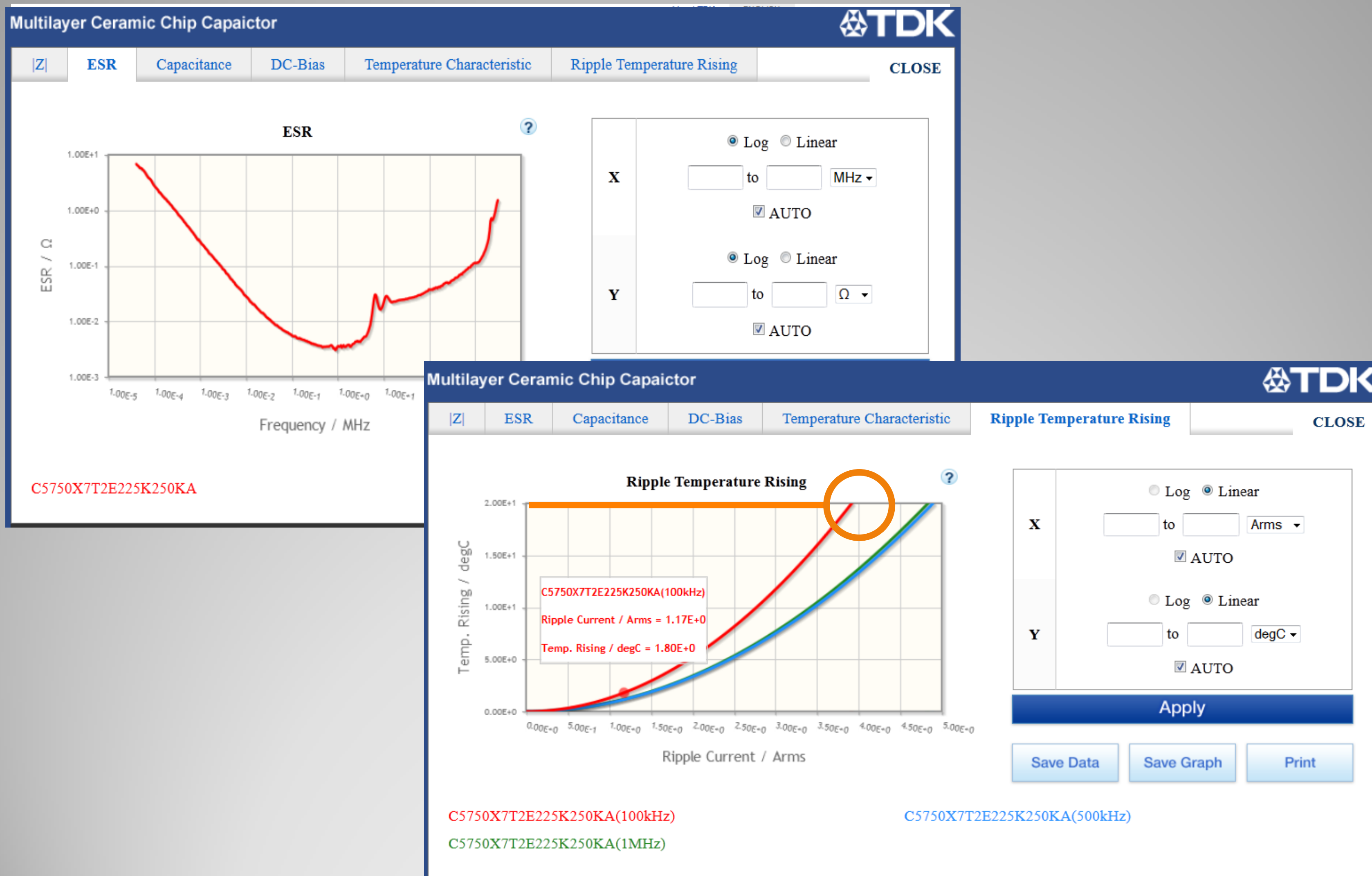
- Voltage and temperature are the two main contributors to an MLCC's reliability over a specific time period.
- AC conditions have a more adverse effect on a DC rated MLCC than a pure DC voltage.
- By not adhering to the guidelines presented into today's presentation, the potential failure mode is an electrical short caused by thermo-electric induced stress.

Failure Detection

Failure Detection

- Through destructive physical analysis (DPA) cross sectioning and inspection under magnification (50 to 200x), this failure mode is detectable by MLCC suppliers.

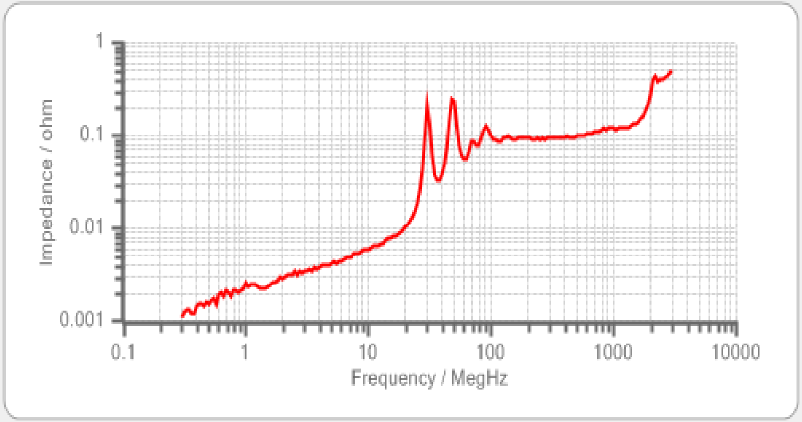


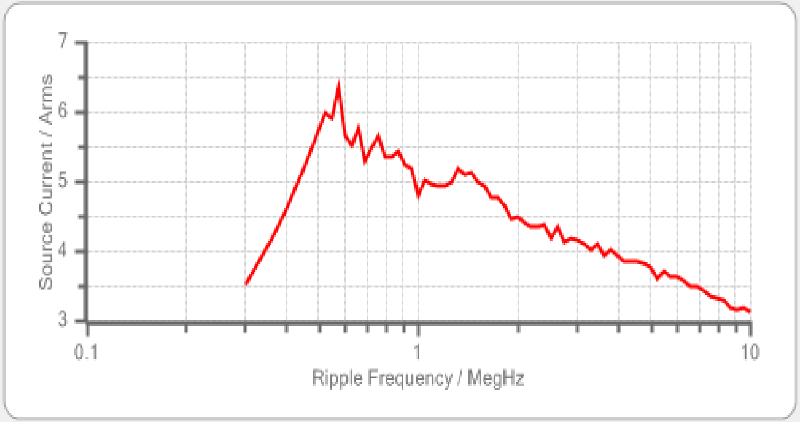


Design Resources

http://product.tdk.com/capacitor/mlcc/en/

- Increased functionality vs website
- Obtain Ripple Current across an entire frequency range (i.e. 300kHz-10MHz)
- Compare up to 16 products at once (vs 4)
- Added feature of series and or parallel component combination





ESR and Ripple Current graphs for a 1812/C0G/50V/100nF/5% MLCC

Design Resources

http://product.tdk.com/en/technicalsupport/seat/

- DC rated MLCCs can prove to be a reliable solution for modern noncritical AC applications, if used with proper design considerations.
- Knowing a product’s maximum AC voltage and current capability are critical to the optimization of this process and this presentation has provided a platform to obtain these values.
- Mitigation of reliability concerns and readily available data will continue to be at the forefront of this movement as the incorporation of volumetric efficient products are considered.
- Suppliers must continue to support data requirements and readily share via their websites and/or design tools

Summary


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
DANKSCHEEN
BIYAN
SHUKRIA
TINGKI
YAQHANYELAY
TASHAKKUR ATU
SUKSAMA
EKHMET
GRAZIE
MEHRBANI
PALDIES
BOLZIN
MERCI
JUSPAXAR
GOZAIMASHITA
EFCHARISTO
KOMAPSUMNIDA
MAAKE
SPASIBO
SPASSIBO
SNACHALHUYA
NUHUN
CHALTU
WABEEJA
MAITEKA
DENKAUJA
HENACHALHYA
SIKOMO
MERASTAWHY
GAEJTHO
TAVTAPUCH
MEDAWAGSE
AGUYJE
FAKAAUE
MINMONCHAR
LAH

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