Loss Modeling of Ceramic Capacitors Under High DC Bias Voltage and AC Current Ripple in High Density Power Converters

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University of California, Berkeley

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PSMA/PELS Capacitor Workshop

Acknowledgment

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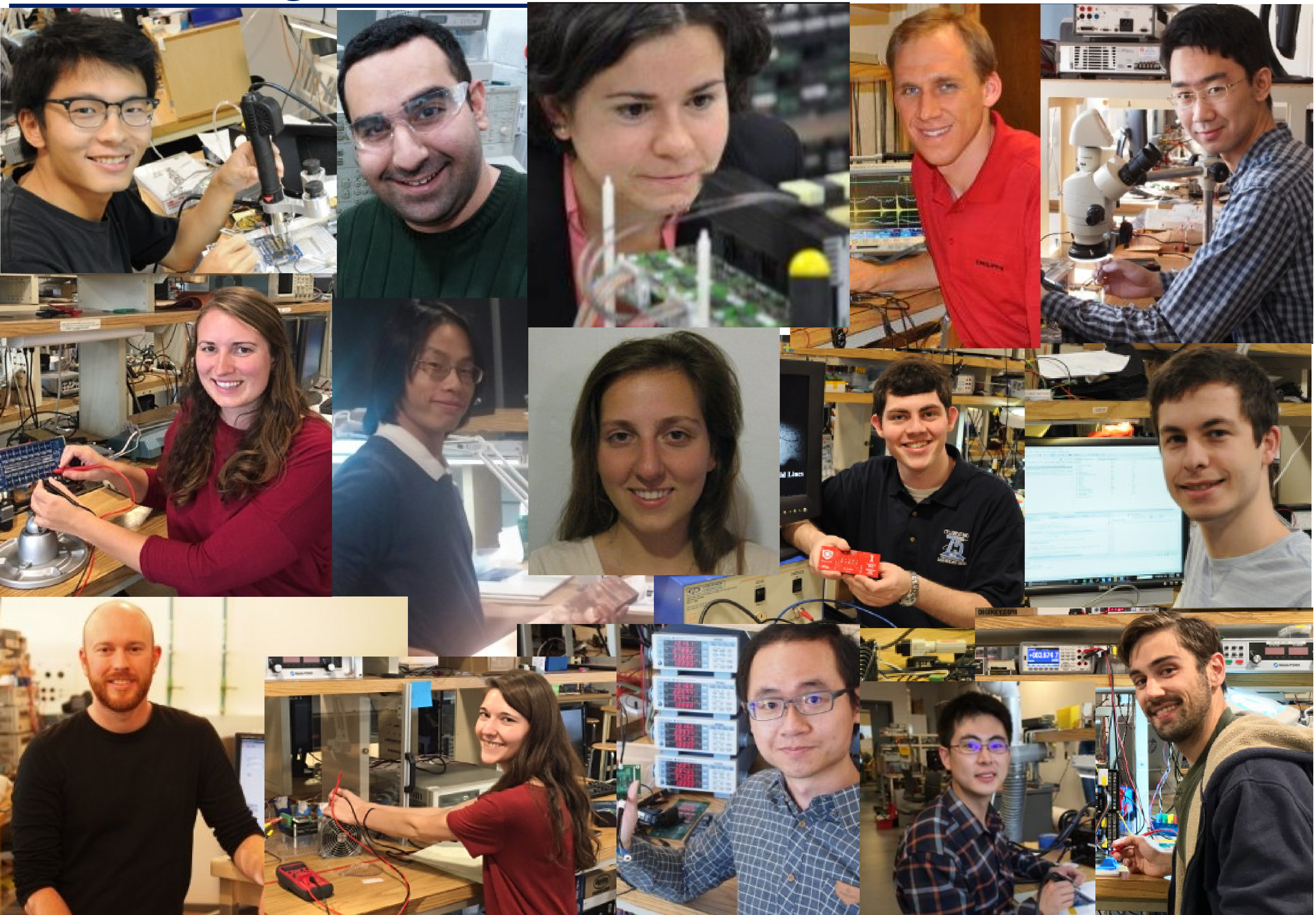

Outline

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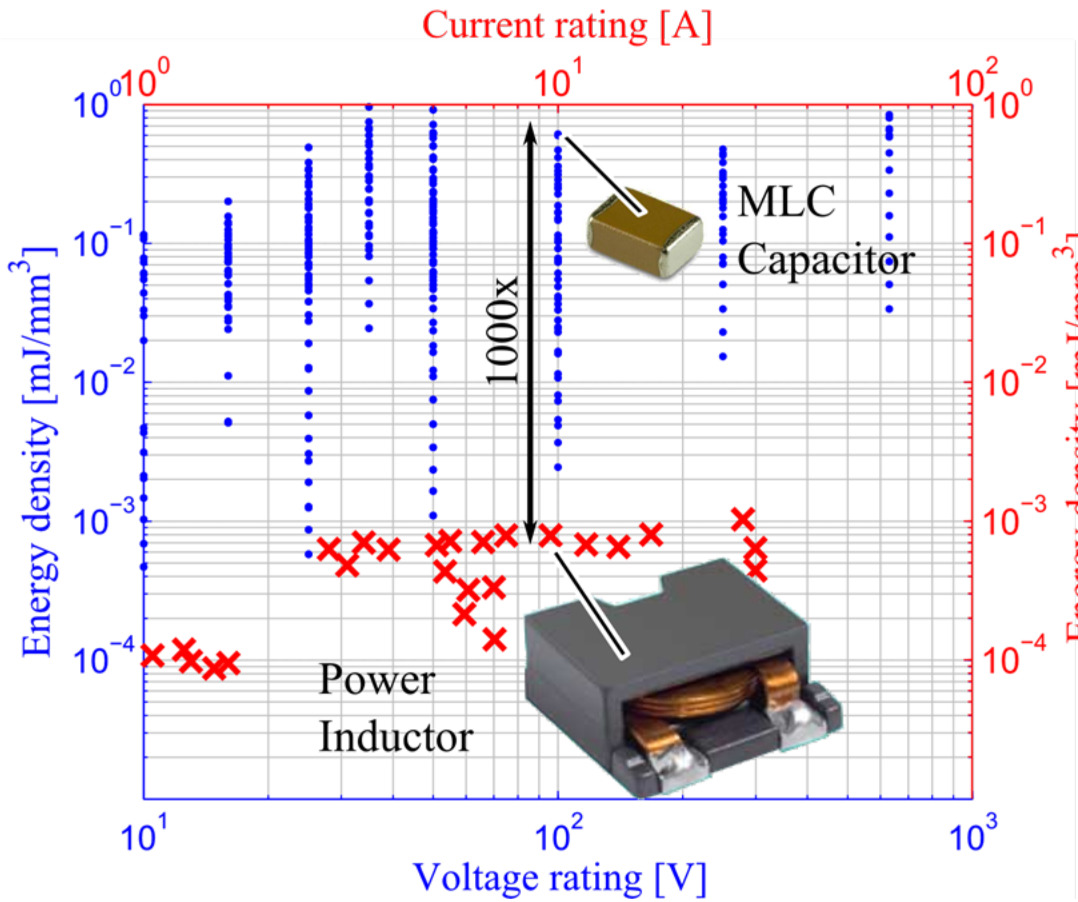
- Introduction and Motivation
  - Why capacitors as energy transfer element?
  - The need for better loss models under realistic conditions
- Loss measurements
  - Calorimetric based MLCC characterization.
- Results and modeling of MLCC.
- Next steps and conclusion.

Why Capacitors?



Survey of Inductors and Capacitor Energy Density [1]

Comparison showing ~1.5mJ of energy storage in a capacitor versus an inductor. (Picture to relative size)

[1] S. Qin, Y. Lei, C. Barth, W. Liu and R. C. N. Pilawa-Podgurski, "A high-efficiency high energy density buffer architecture for power pulsation decoupling in grid-interfaced converters," *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, Montreal, QC, 2015, pp. 149-157.

Example using capacitors for energy transfer

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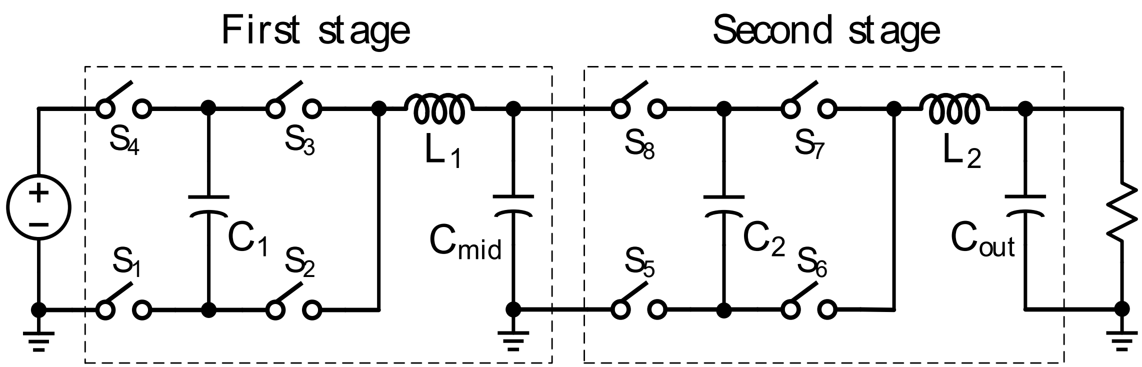
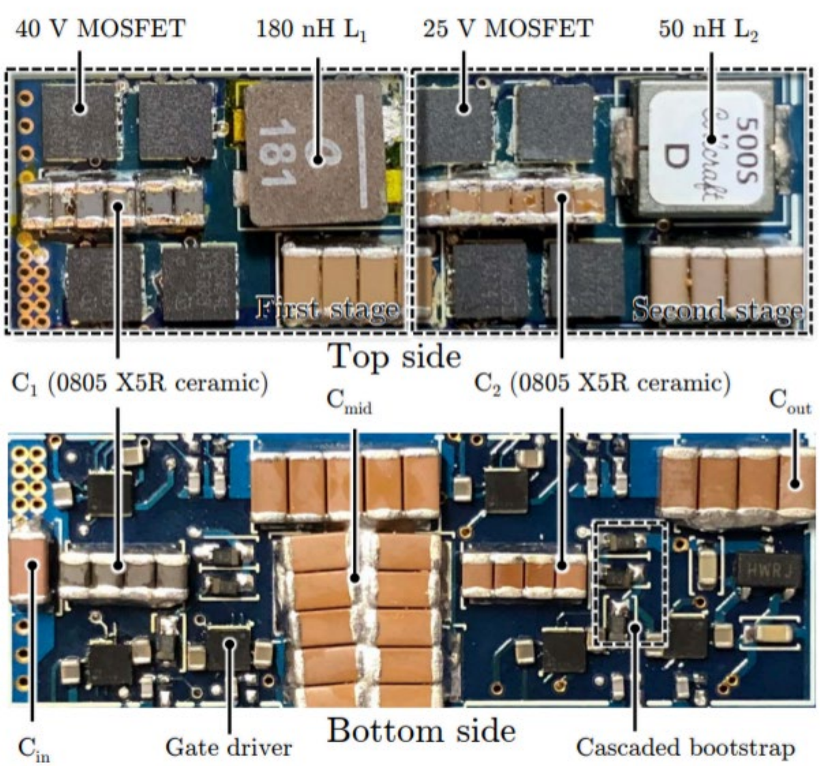
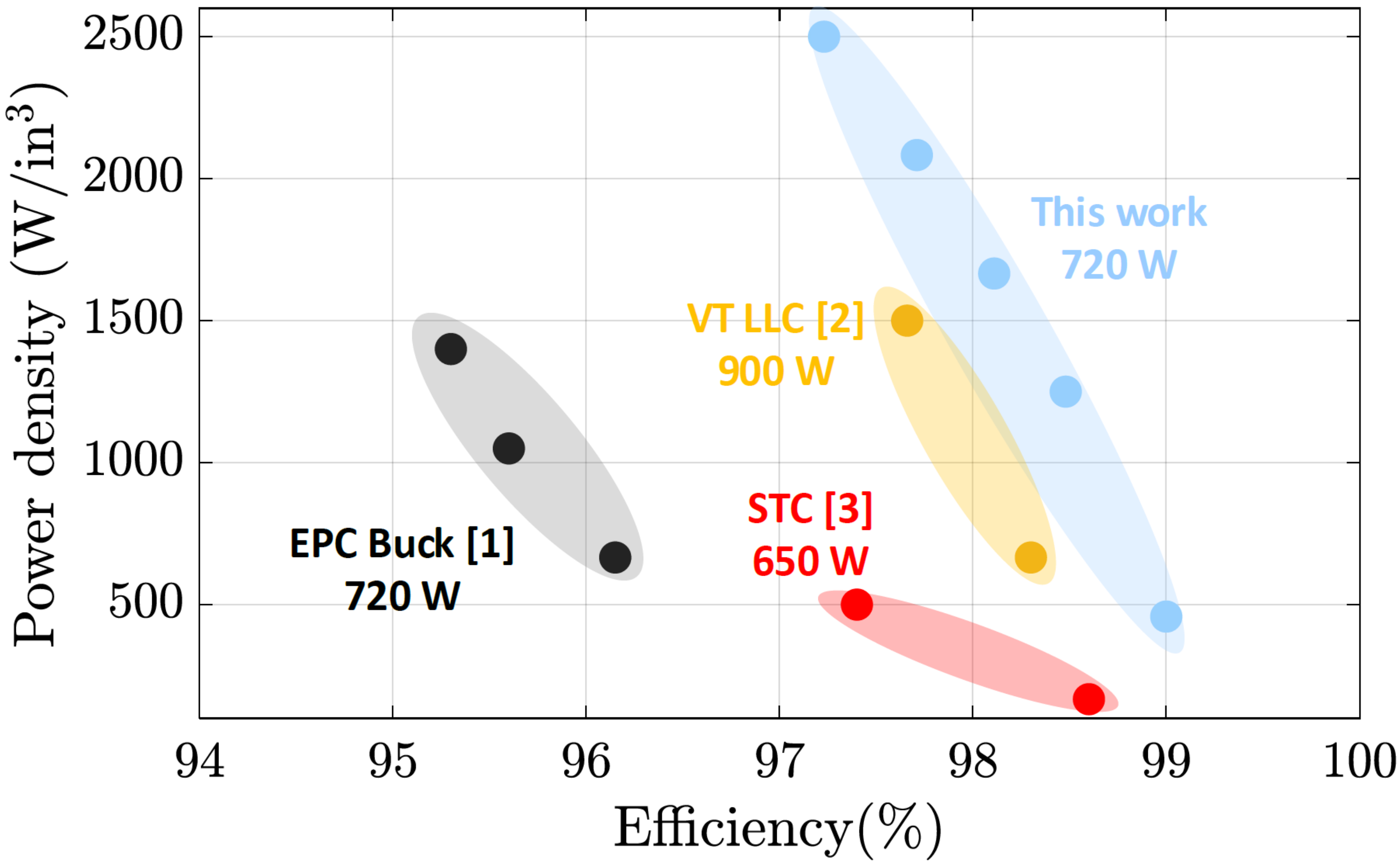




Input voltage range	36 – 60 V
Conversion ratio	4 : 1
Output current	60 A
Power density	2500 W/in^3
Peak efficiency	99 %

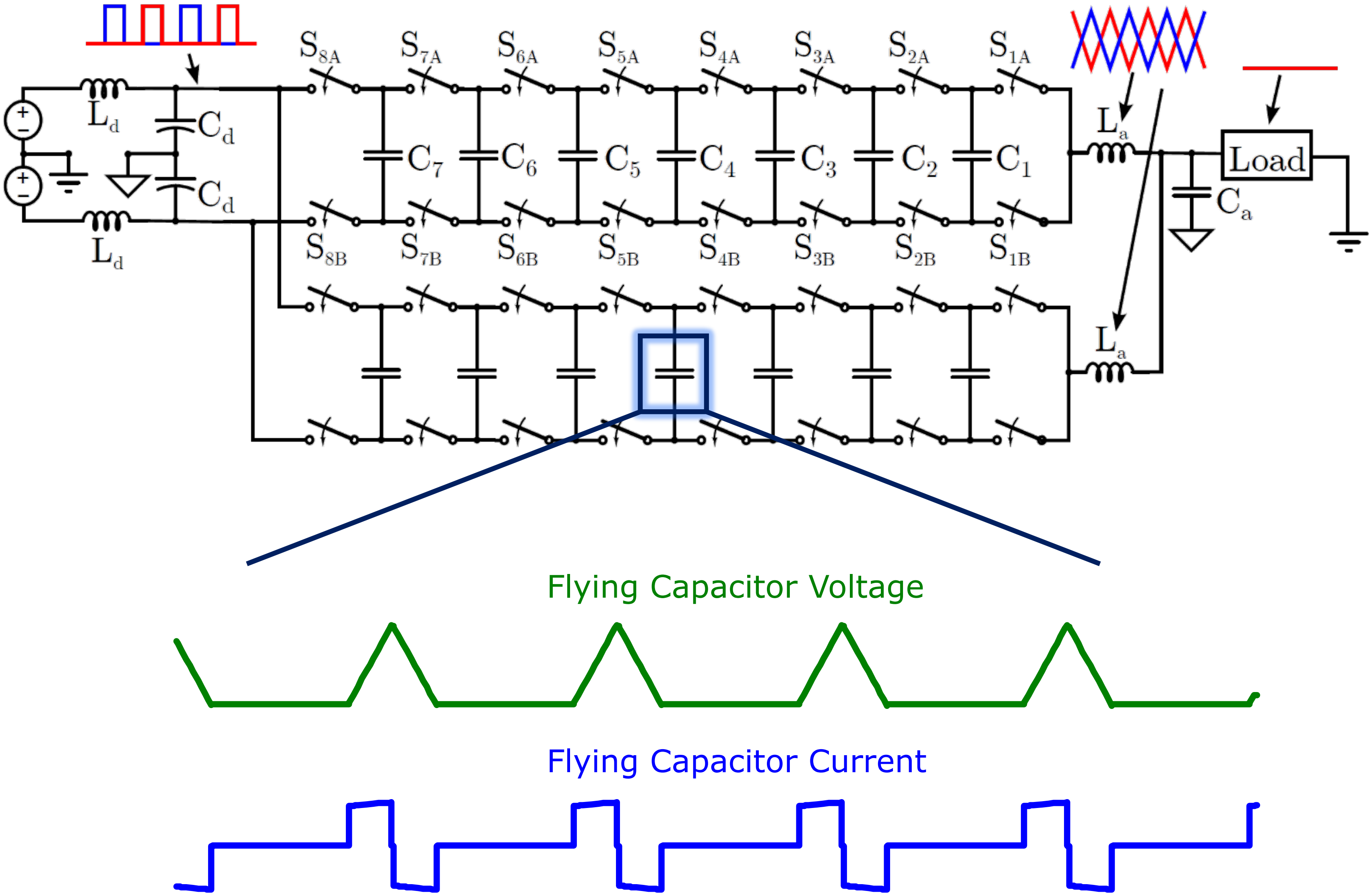
Z. Ye, Y. Lei, R.C.N. Pilawa-Podgurski, "A 48-to-12 V Cascaded Resonant Switched-Capacitor Converter for Data Centers with 99% Peak Efficiency and 2500 W/in3 Power Density", APEC 2019 (Tuesday Session, T01)

Comparison with the state-of-the-art



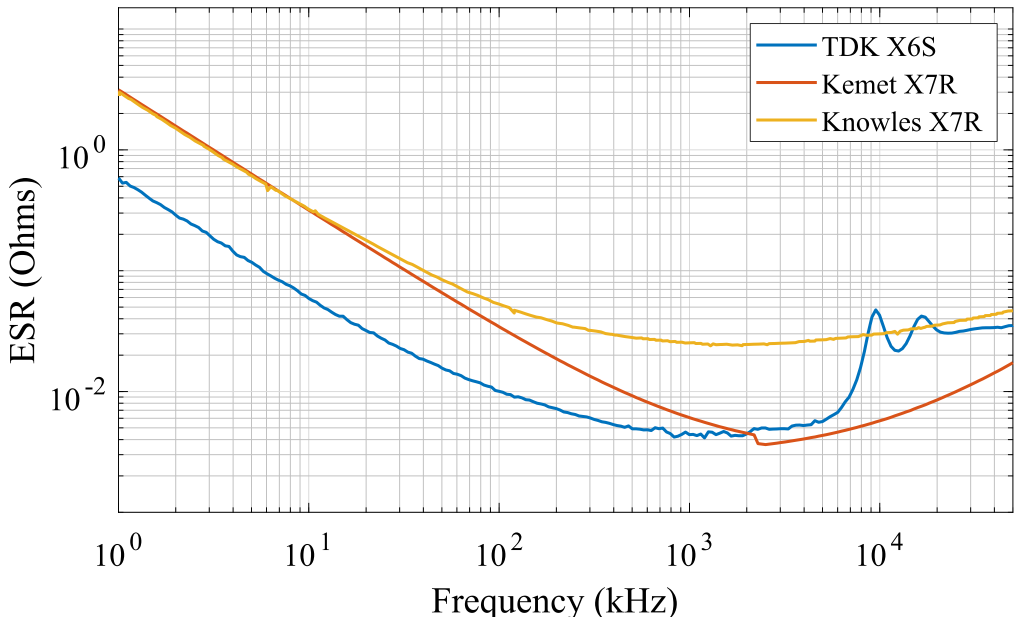
[1] D. Reusch, S. Biswas and Y. Zhang, "System Optimization of a High Power Density Non-Isolated Intermediate Bus Converter for 48 V Server Applications," in IEEE Transactions on Industry Applications. doi: 10.1109/TIA.2018.2875387
[2] M. H. Ahmed, M. A. de Rooij and J. Wang, "High-Power Density, 900-W LLC Converters for Servers Using GaN FETs: Toward Greater Efficiency and Power Density in 48 V to 6\/12 V Converters," in IEEE Power Electronics Magazine, vol. 6, no. 1, pp. 40-47, March 2019.
[3] S. Jiang, S. Saggini, C. Nan, X. Li, C. Chung and M. Yazdani, "Switched Tank Converters," in IEEE Transactions on Power Electronics. doi: 10.1109/TPEL.2018.2868447

Capacitor operating conditions



Motivation

- Power losses can be reduced to an equivalent series resistance (ESR).
- These losses are dependent on a number of operating conditions.
  - Temperature, frequency, AC amplitude, DC bias, excitation shape/harmonics
- Most data sheets only detail losses under small signal, no bias sinusoidal excitations.



Motivation

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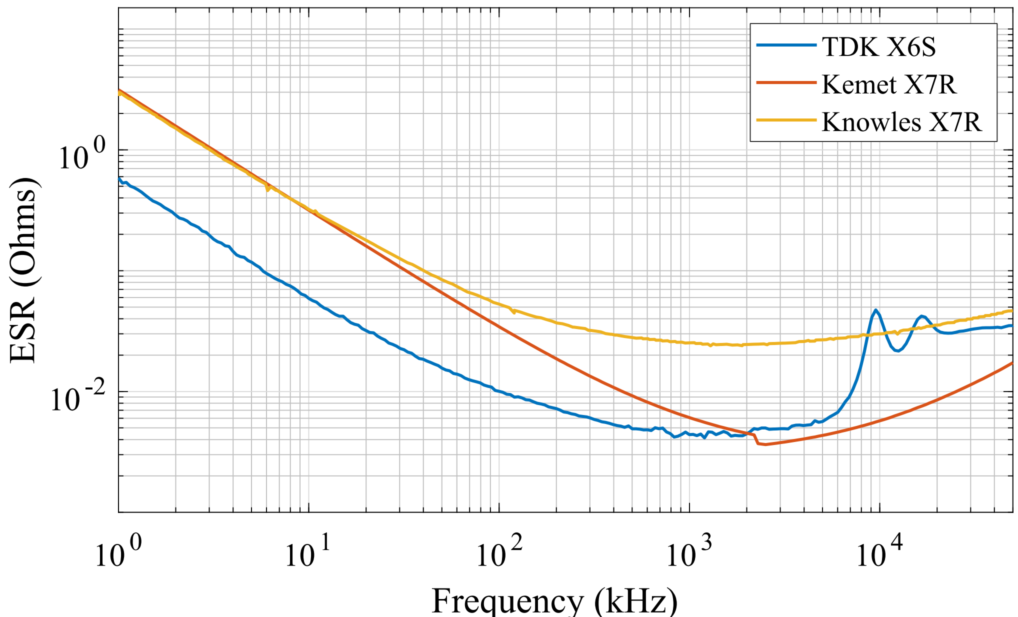
- Operating conditions which effect ESR
  - Temperature
  - Frequency
  - AC amplitude
  - DC bias
  - Excitation shape/harmonics



Motivation

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  - ✓ Temperature
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  - ☐ DC bias
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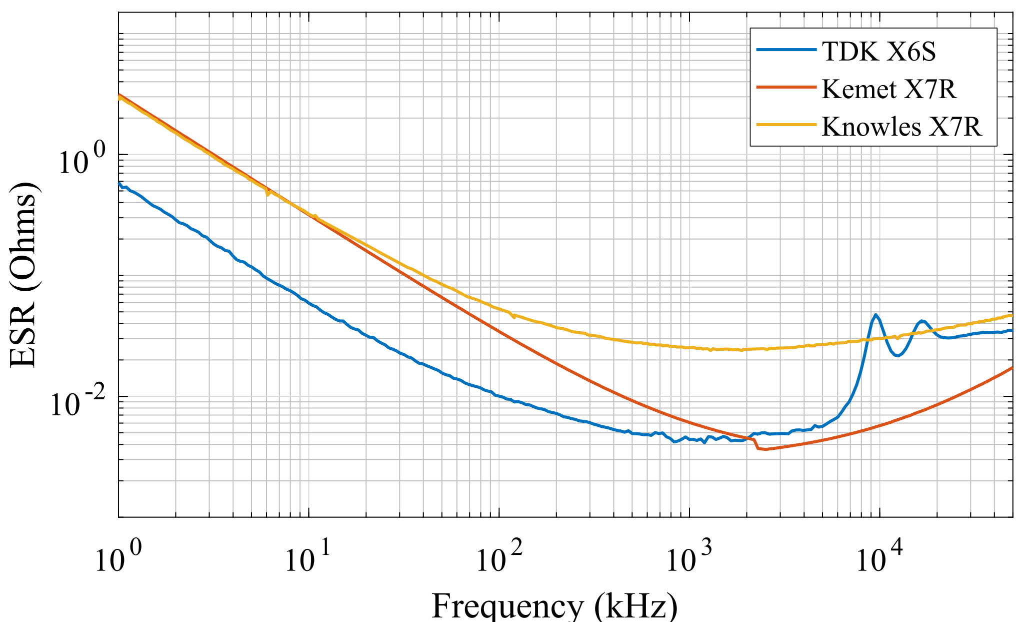

Motivation for Calorimetric Measurements

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- Desired measurement specifications
  - Current: 6 A RMS
  - Voltage: 400 V (Δ_V = 10 V)
  - *Transferred* Power: 2.4 kW
  - Power *loss*: ~1 W

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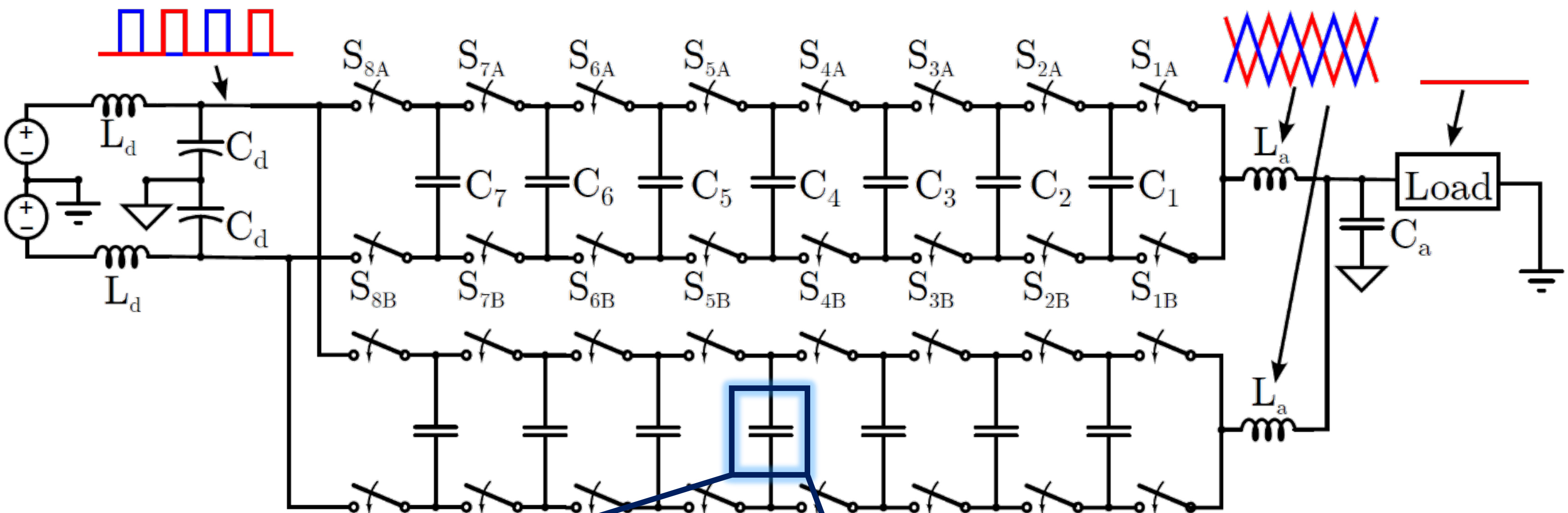
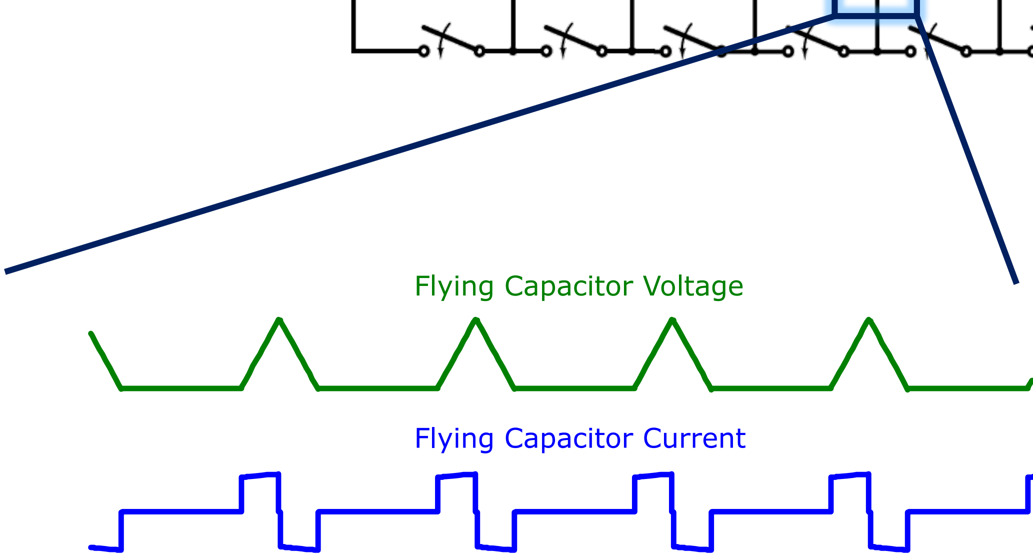
- Electrical Measurement Accuracy
  - 500 kHz: ± 10.2 W

Yokogawa WT3000

Capacitor operating conditions





- ❑ High Harmonic Excitation
- ❑ Hundreds of kHz Frequency
- ❑ Large AC Excitation
- ❑ DC Voltage Bias

Electrical Test Configuration

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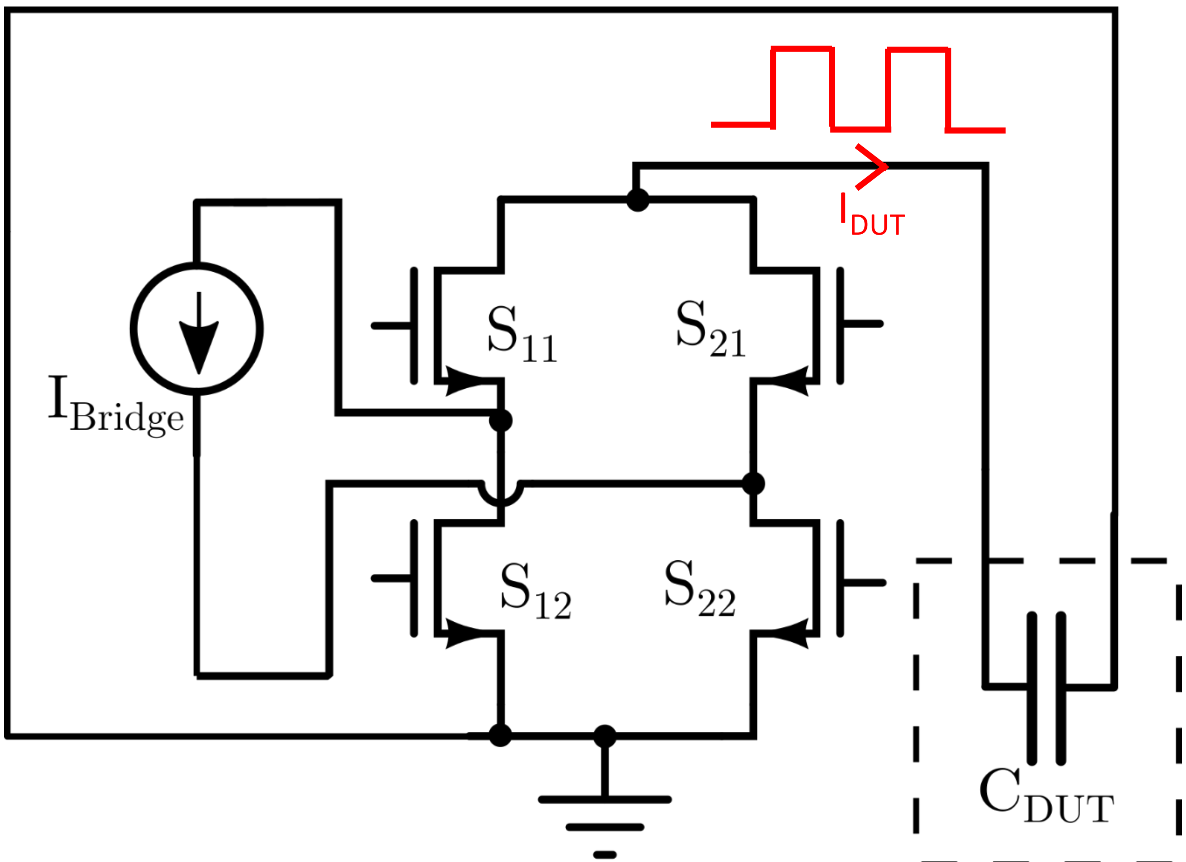

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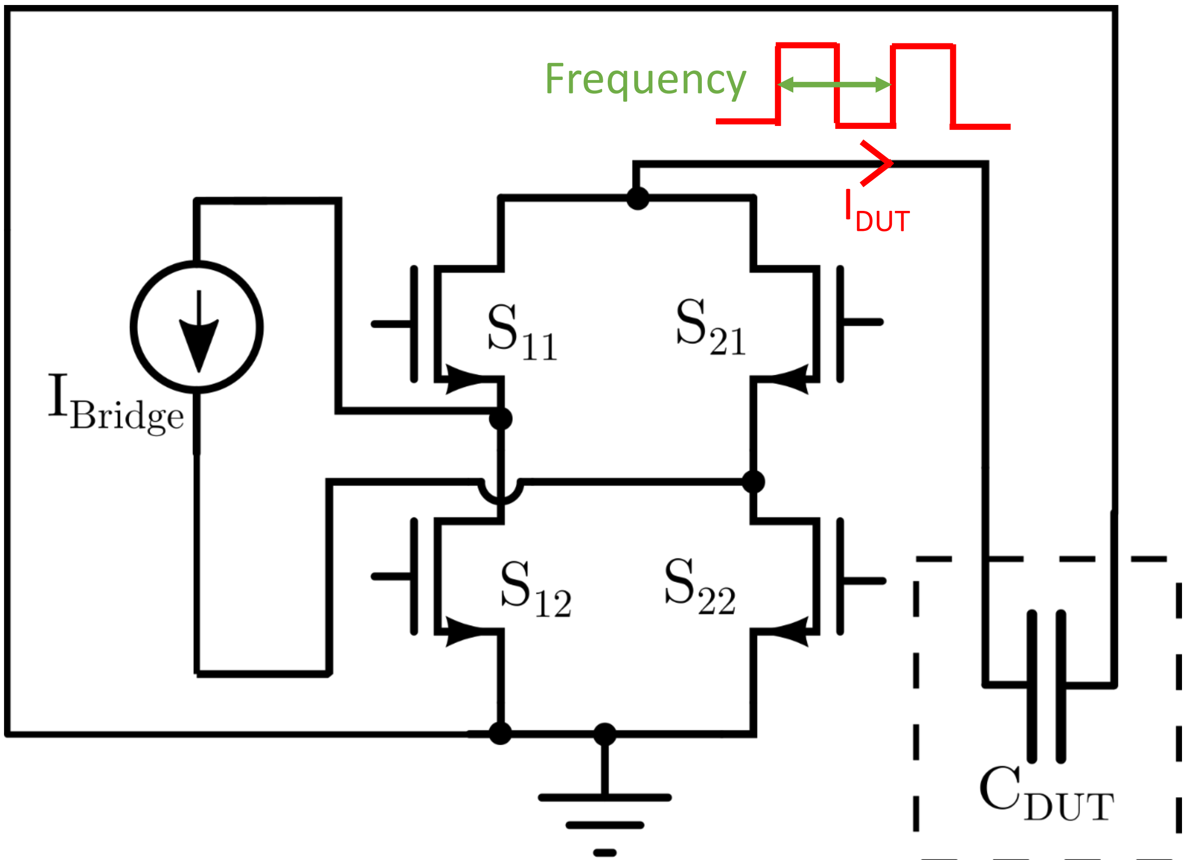

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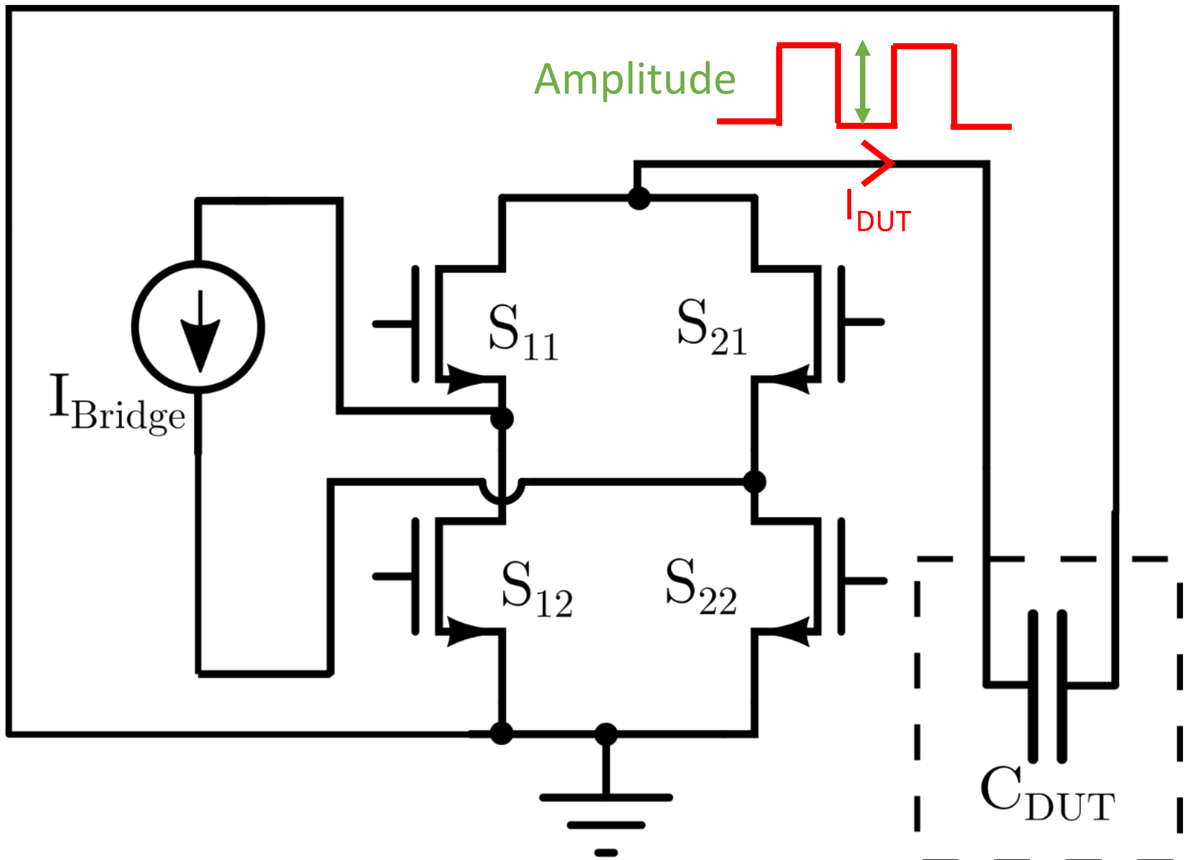

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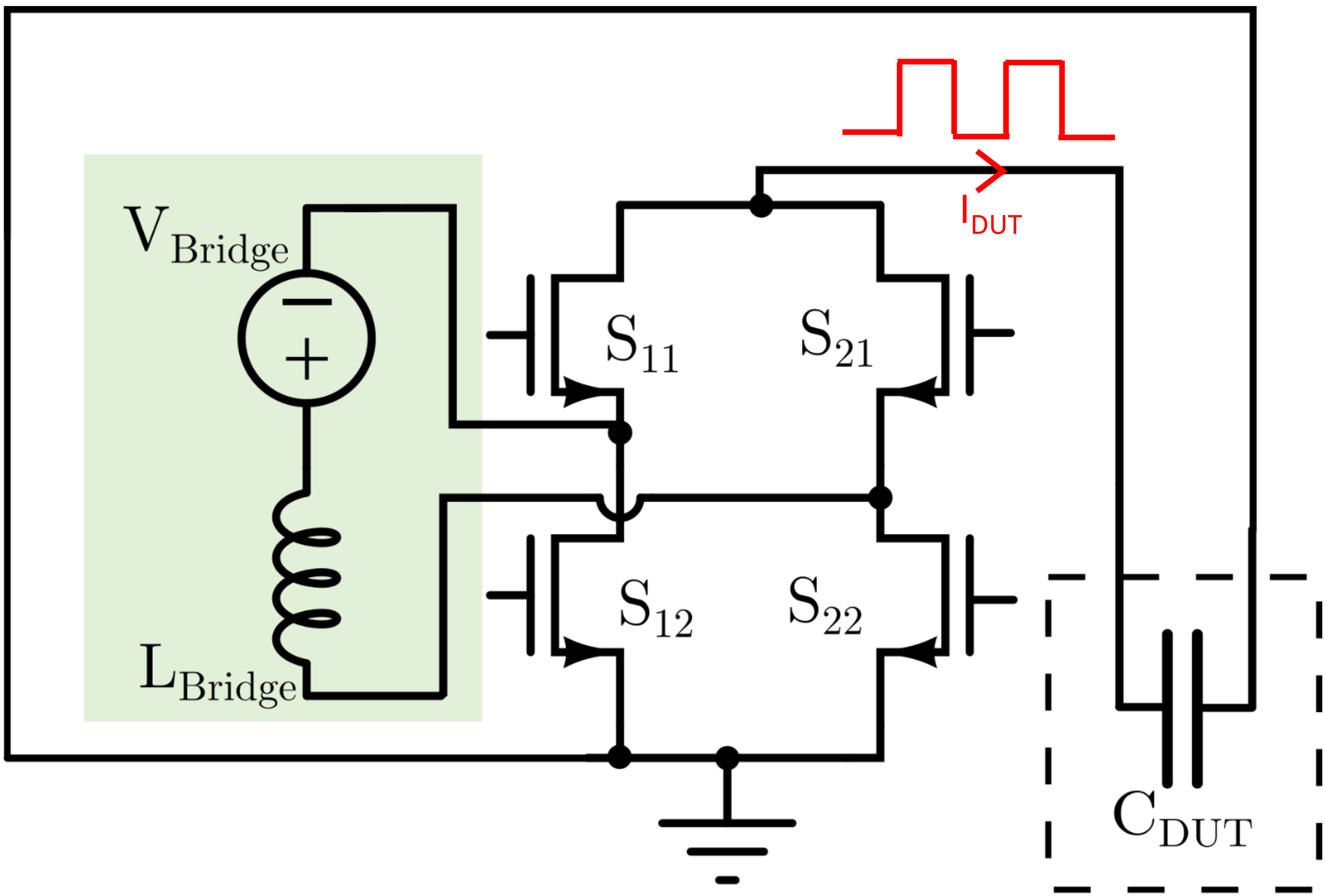

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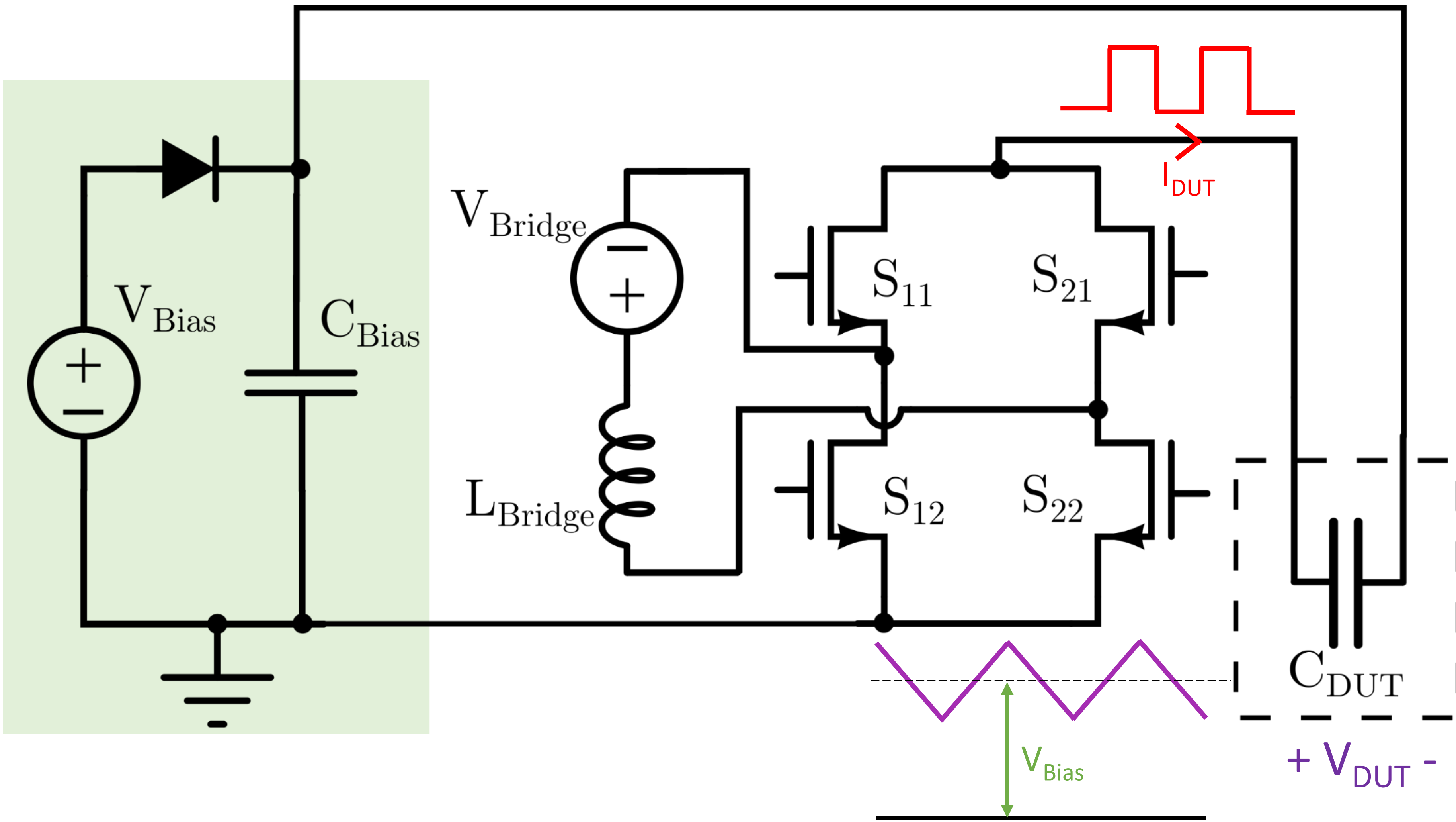

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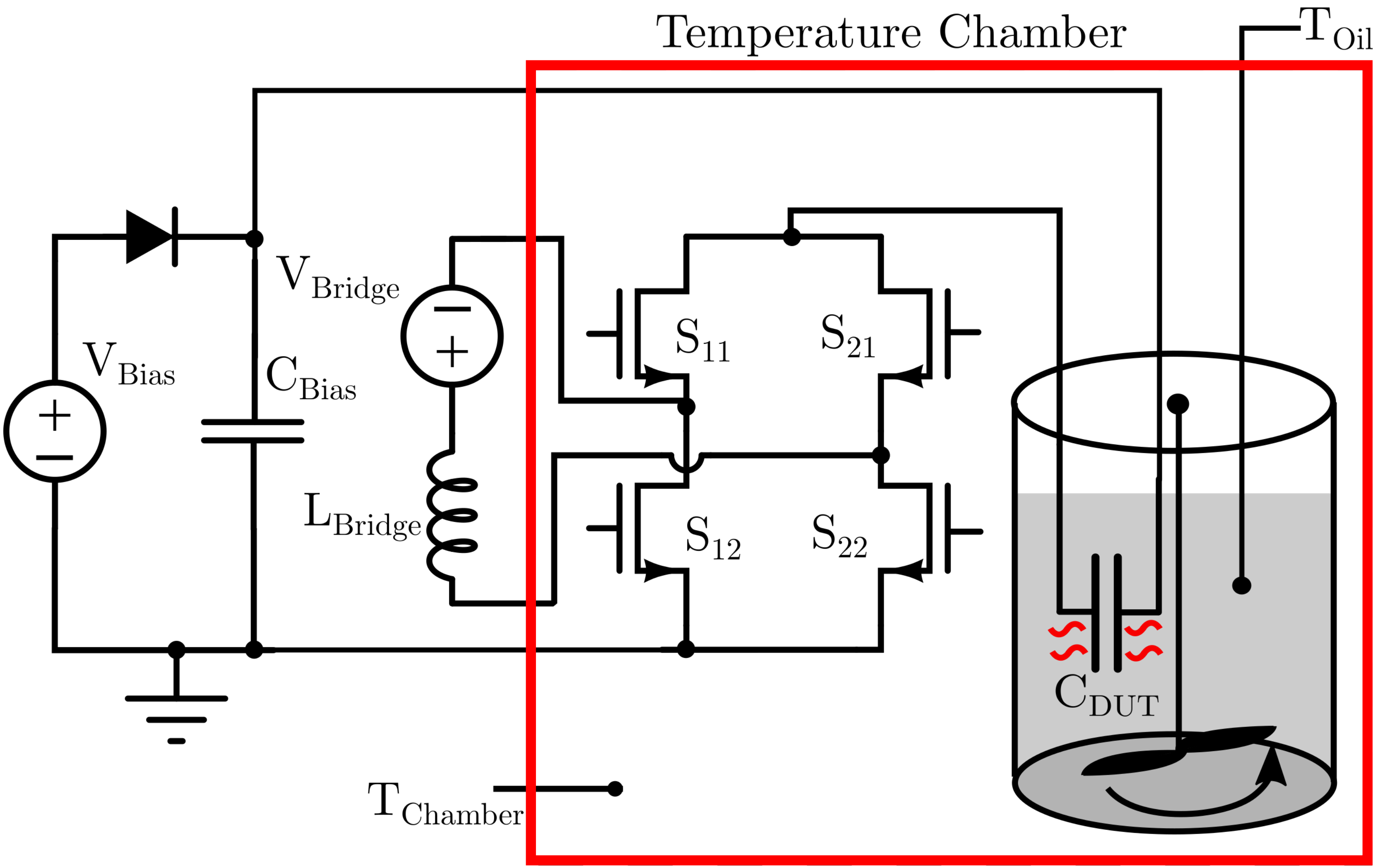
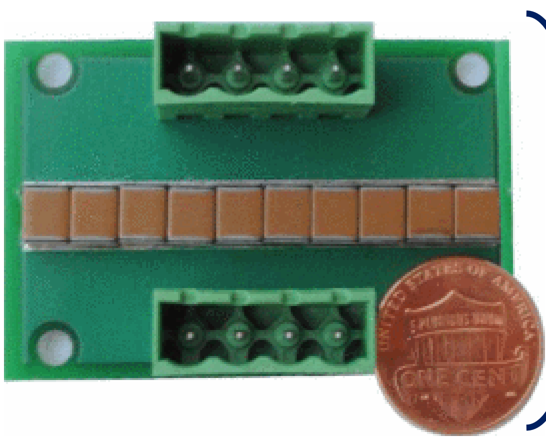
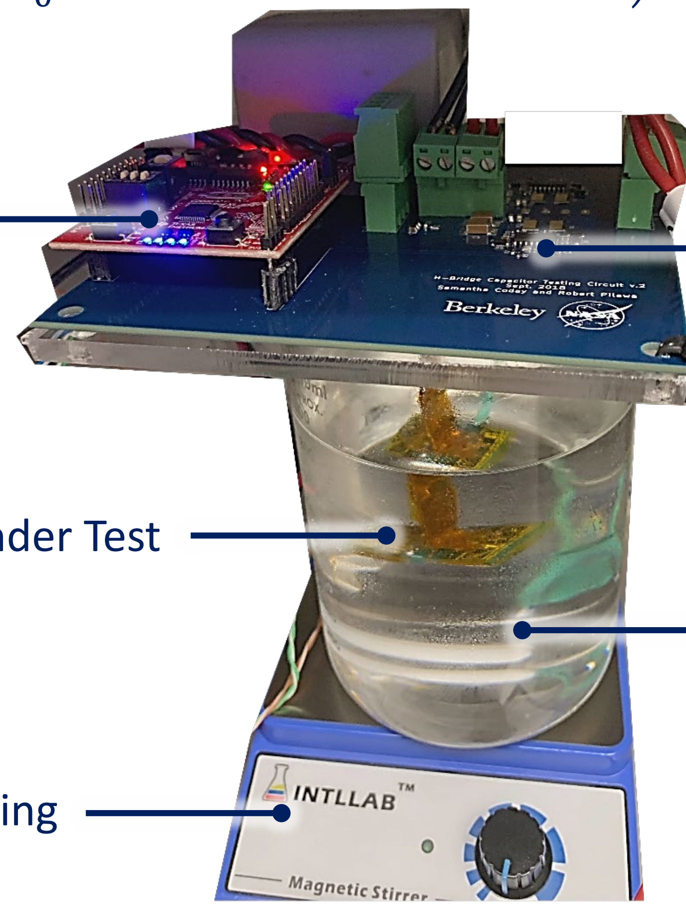


Calorimetric Theory [1]

- Rise in temperature of oil is measured to determine power dissipated by device under test (DUT).

$$P_{diss} = \frac{1}{T_{final}} \left(k_{oil}\, \Delta temp + \int_0^{T_{final}} \frac{temp_{oil} - temp_{amb}}{R}\, dt \right)$$





[1] G. S. Dimitrakakis, E. C. Tatakis, and A. C. Nanakos, "A simple calorimetric setup for the accurate measurement of losses in power electronic converters," in Proceedings of the 2011 14th European Conference on Power Electronics and Applications, Aug 2011, pp. 1–9.

Calorimetric Calibration Testing

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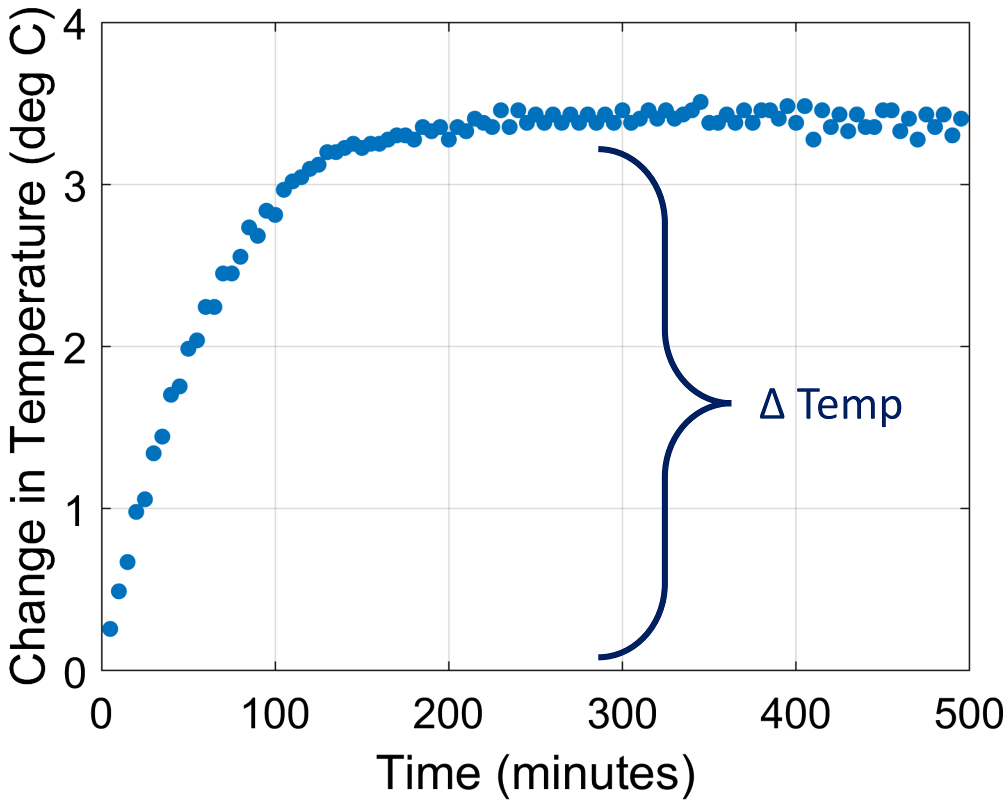
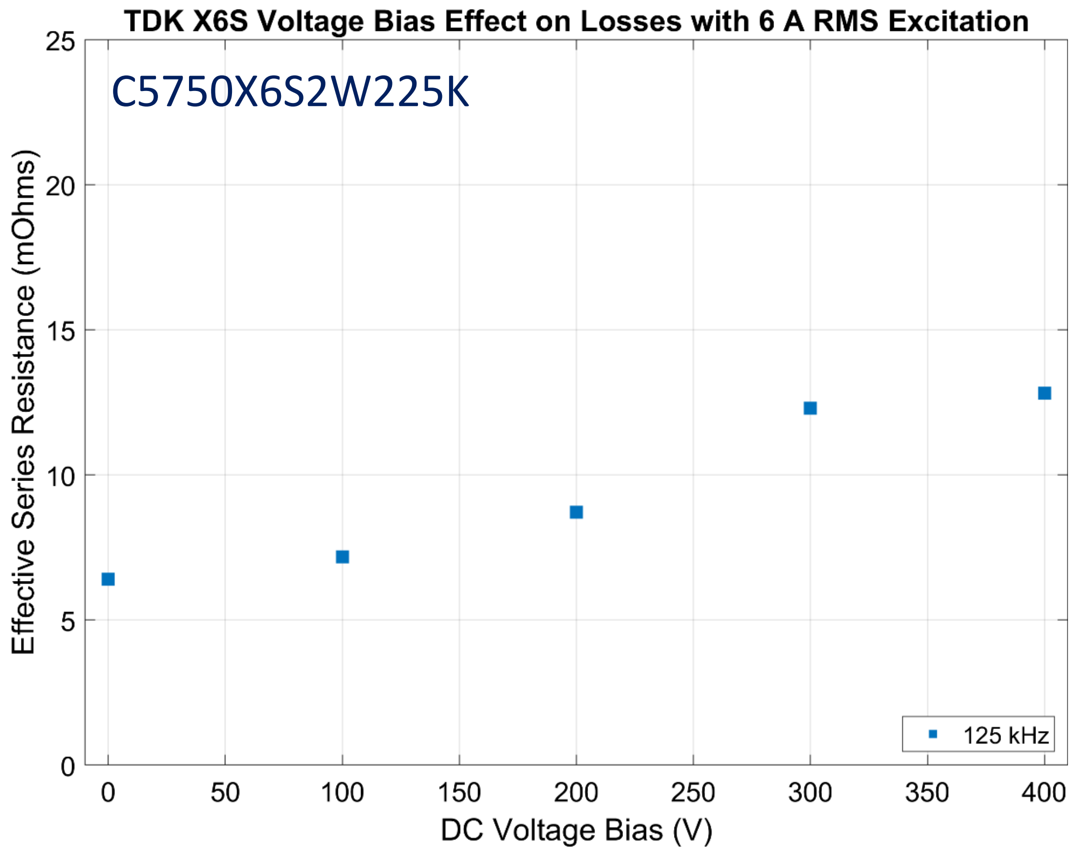
- Resistive testing is used to determine thermal resistivity of set-up, R_{TH}.
- A precision resistor is used to determine accurate power loss.



DC Bias Analysis [1]

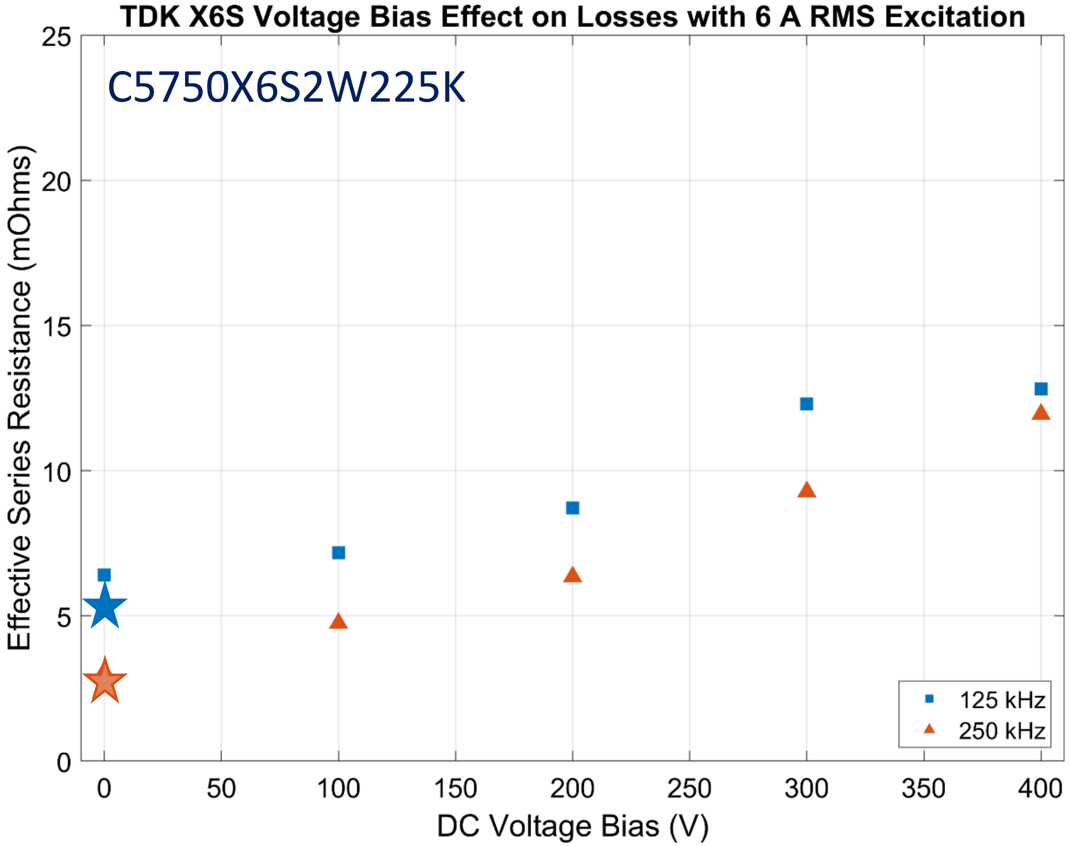
- Measured ESR increases with applied DC bias.
- Relationship is linear allowing for interpolation of operating conditions to approximated losses.



[1] S. Coday, C. B. Barth and R. C. N. Pilawa-Podgurski, "Characterization and Modeling of Ceramic Capacitor Losses under Large Signal Operating Conditions," *2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Padua, 2018, pp. 1-8.

DC Bias Analysis

- Estimated accuracy of measurement is ±0.117 mΩ.
- Results at 0V bias are slightly higher than datasheet values due to high harmonic components[1]



[1] TDK, "C series commercial grade mid voltage (100V to 630V)," Datasheet, Mar. 2015.

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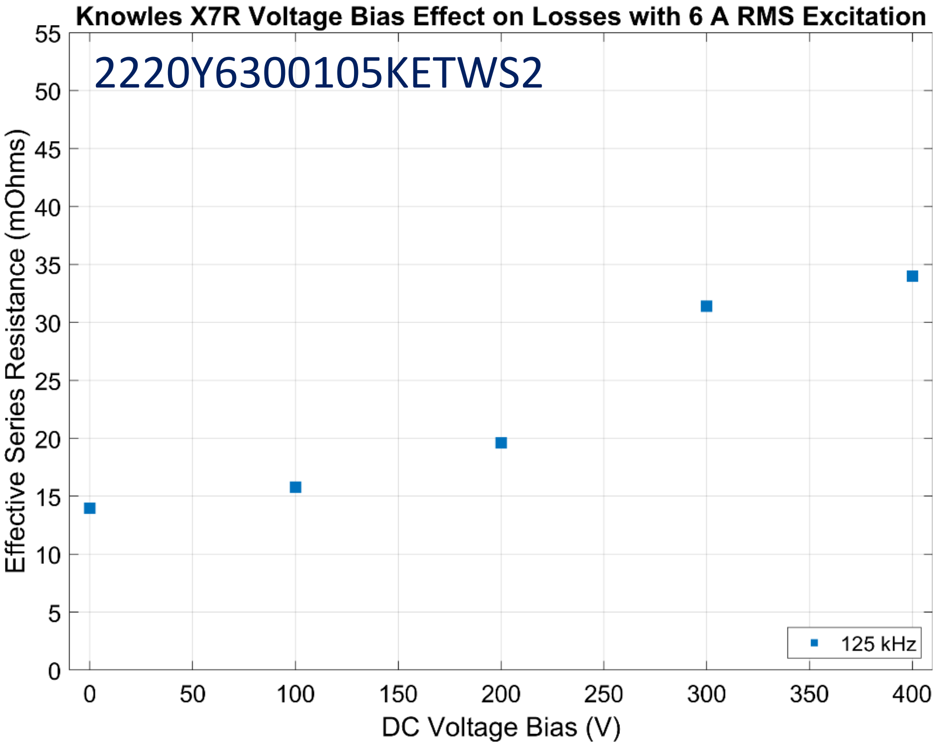

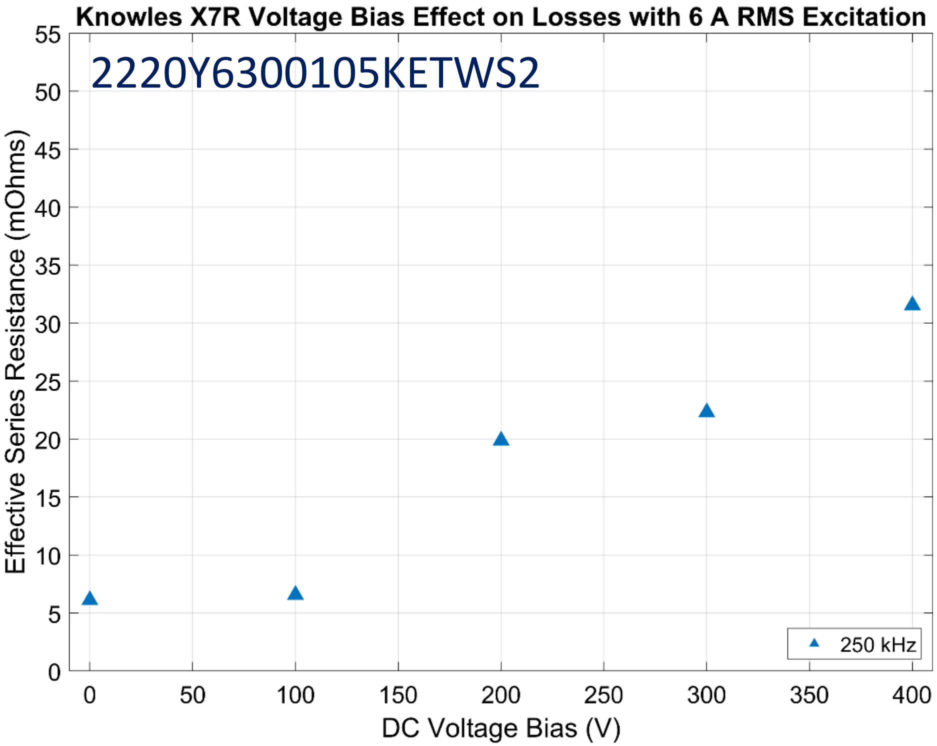

Effect of Current Amplitude on Losses

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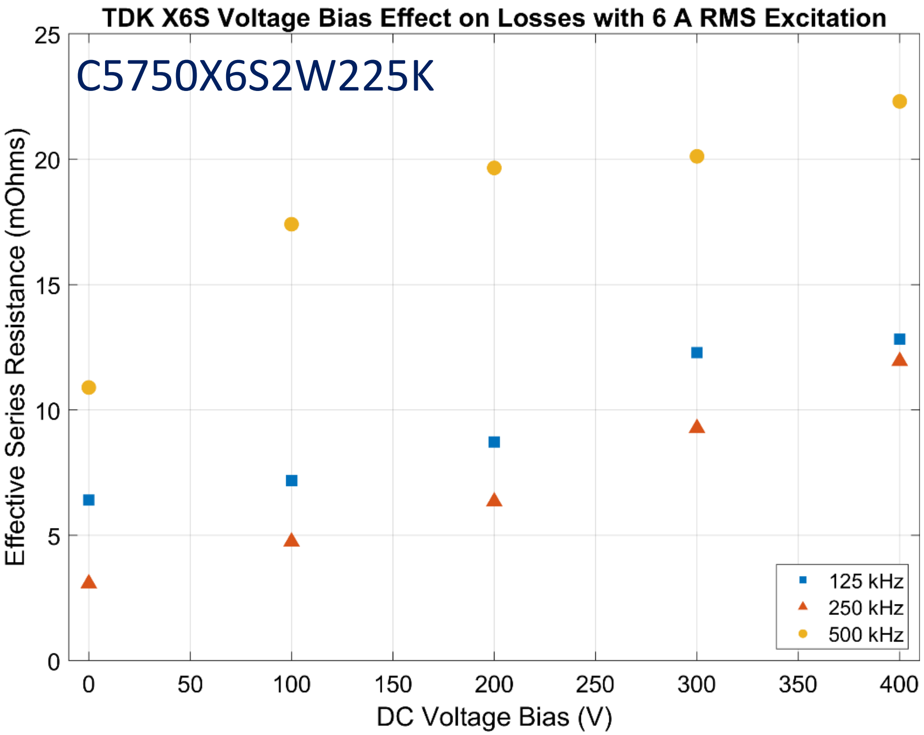
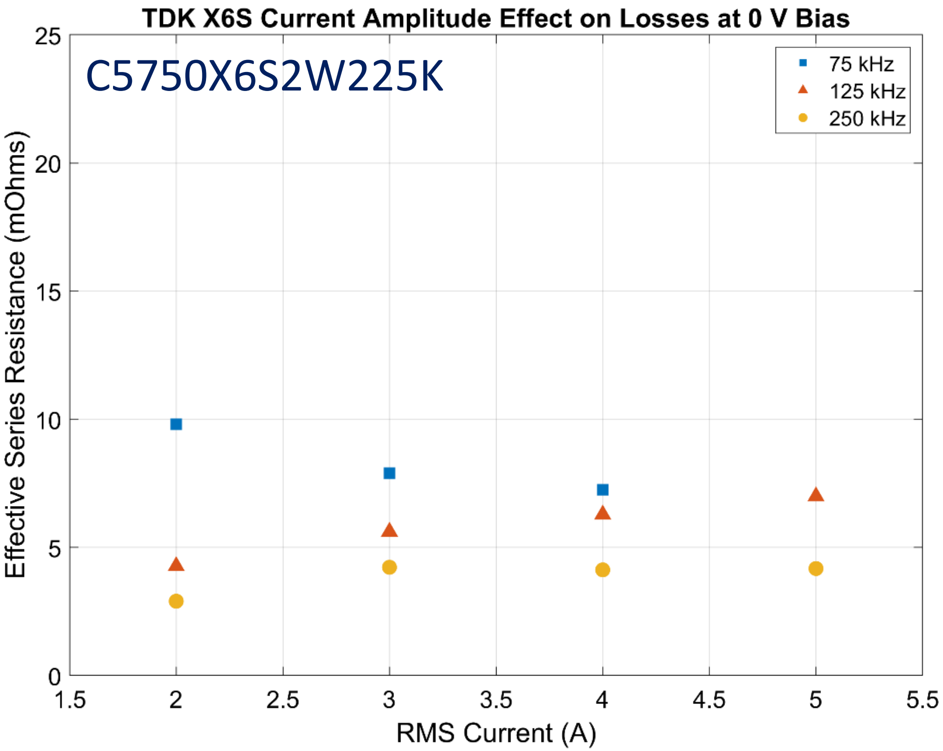
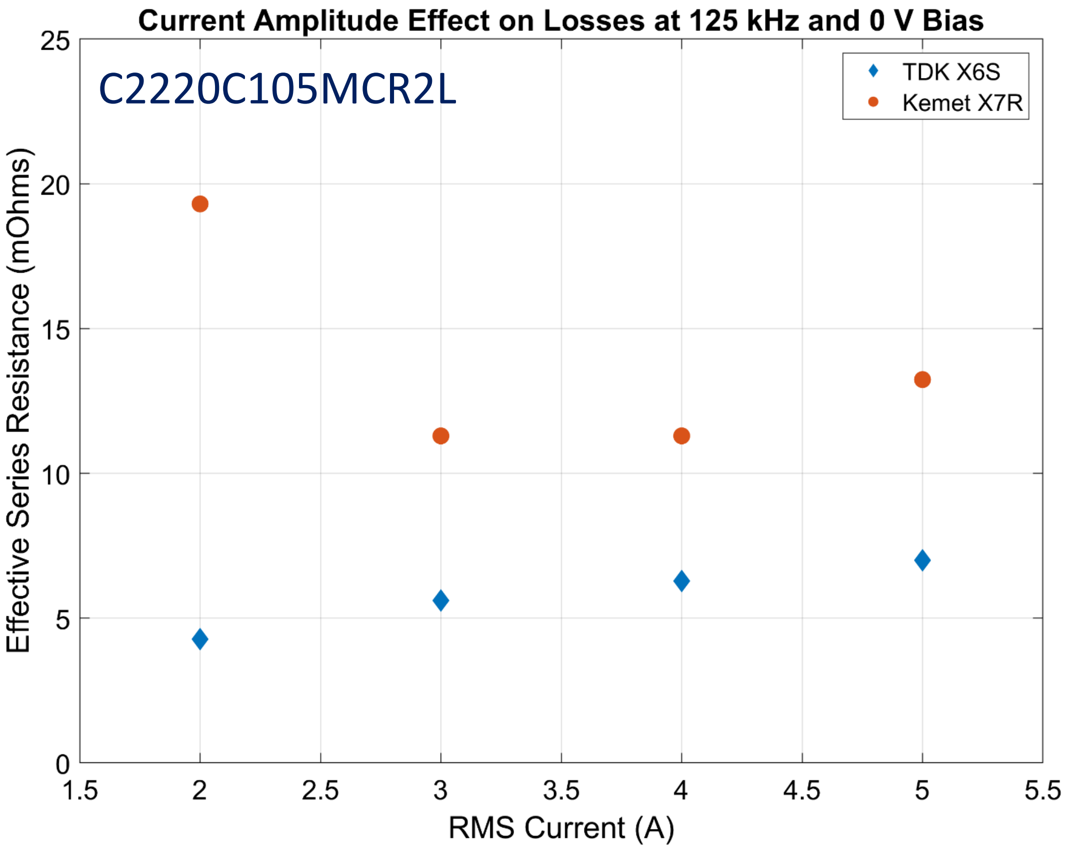
- Measured ESR increases with varying AC amplitude.
- Relative to DC bias dependent loss the AC amplitude has little effect on ESR.





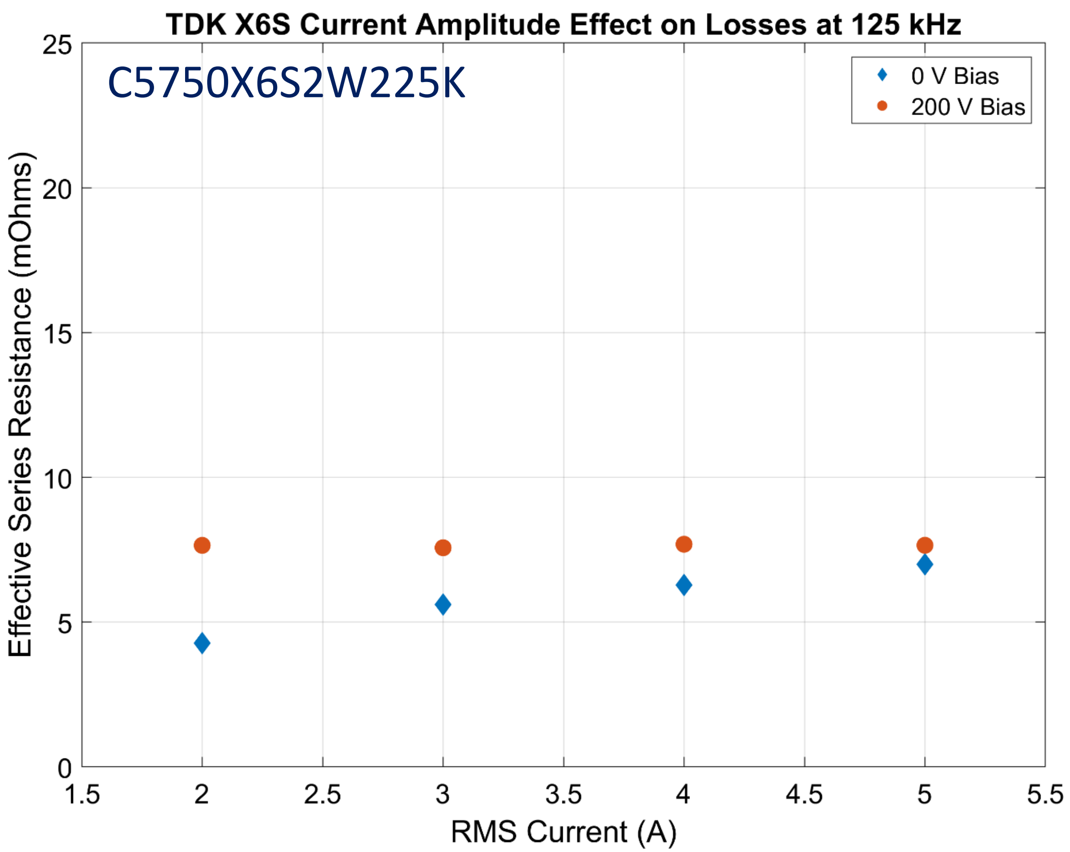
Comparison of Capacitors with Current Loss

- The AC current impact was tested on capacitors with different dielectrics as well as manufacturers.



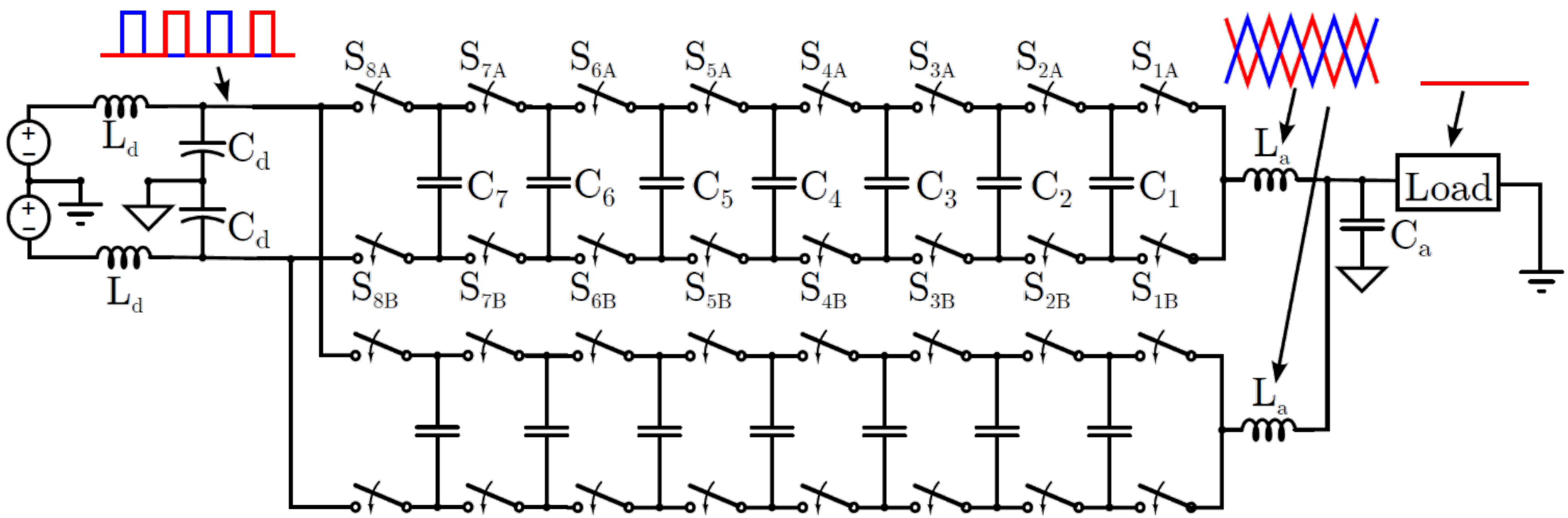
Varying Current loss and DC Bias

- With varying current amplitude the DC bias still shows dominant effect on ESR.



Application of Results

Capacitor Manufacturer	Capacitor Type	Capacitor De-rating (at 400 V)	ESR increase (at 400 V, 125 kHz)
TDK	X6S	80%	200%
Knowles	X7R	82%	243%
Kemet	X7R	72%	142%



Conclusions

- Capacitor losses depend on:
  - ✓ Temperature
  - ✓ Frequency
  - ✓ AC amplitude
  - ✓ DC bias
  - ❑ Excitation shape/harmonics
- DC bias in particular can greatly affect the ESR, which must be taken into account in power converter design.

How can industry best measure/report these dependencies?

Can we use this data to design lower loss capacitors for real-world conditions?

Acknowledgements

- This work was partially sponsored by NASA