HIGH INPUT VOLTAGE DESIGNS

By Cody Clarksean

AGENDA

- What is a High voltage input for Switch Mode Power Supplies
- High Voltage Challenges
  - Magnetics
  - Bulk Capacitors
  - Transistors
- Helpful tools
- Conclusion

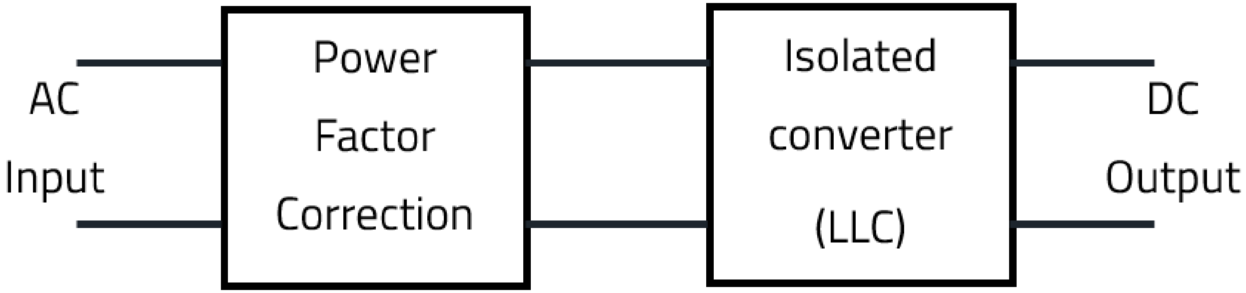
WHAT IS A HIGH INPUT

WHAT IS A HIGH INPUT

Defining

- Single Phase AC inputs can vary based on the design requirements
  - North American (108-132 VAC)
  - European (207-253 VAC)
  - Universal (85-265 VAC)

- High input can occur with variable systems
  - 480 VAC – Line to Line connection from 3 phase
  - 600 VAC – Line to Line connection from 3 phase



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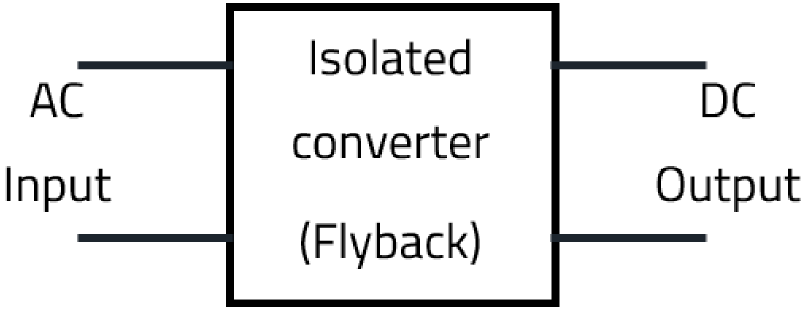

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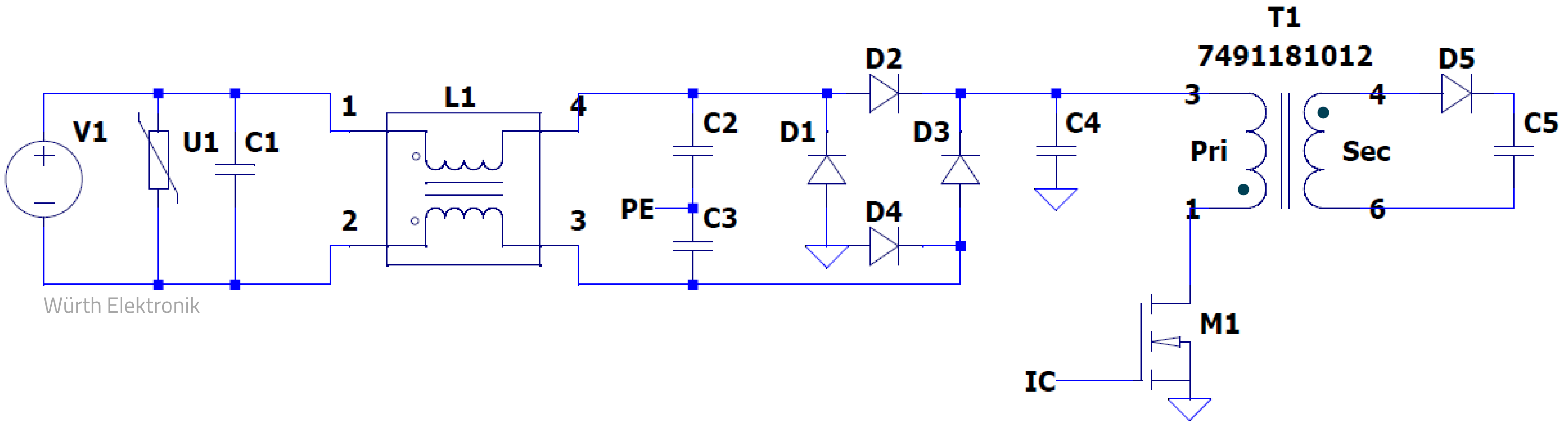
WHAT IS A HIGH INPUT

Front end of AC/DC Flyback Circuit



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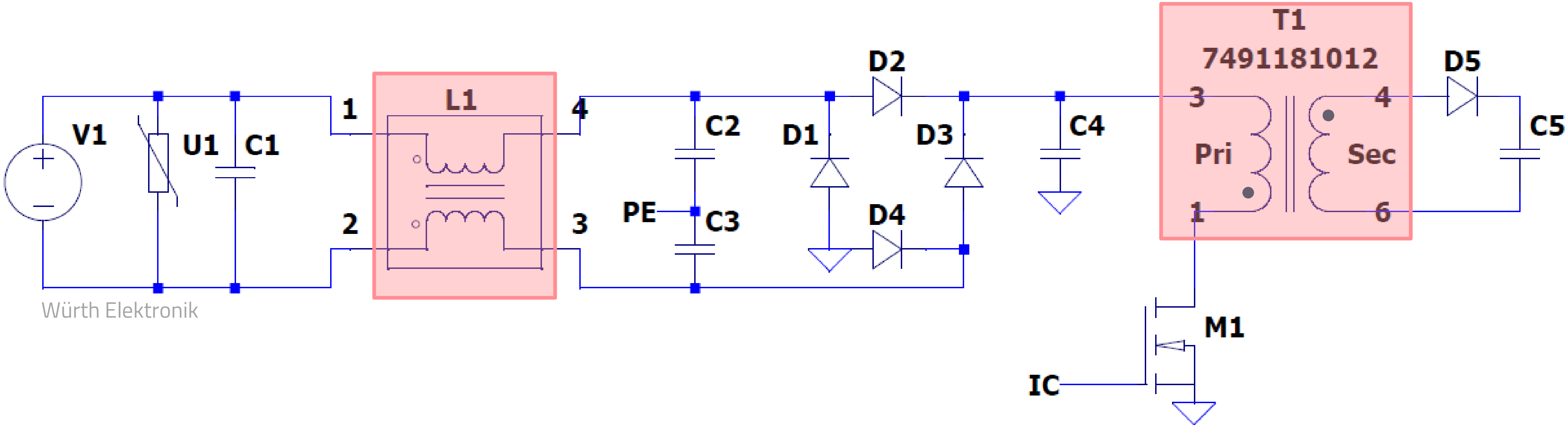

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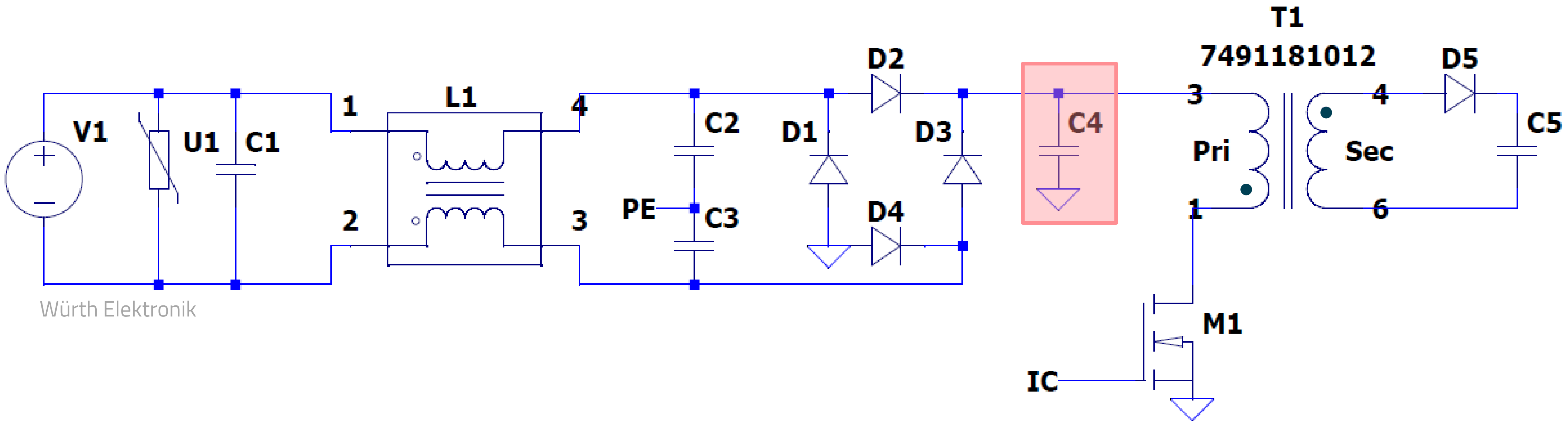

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WHAT IS A HIGH INPUT

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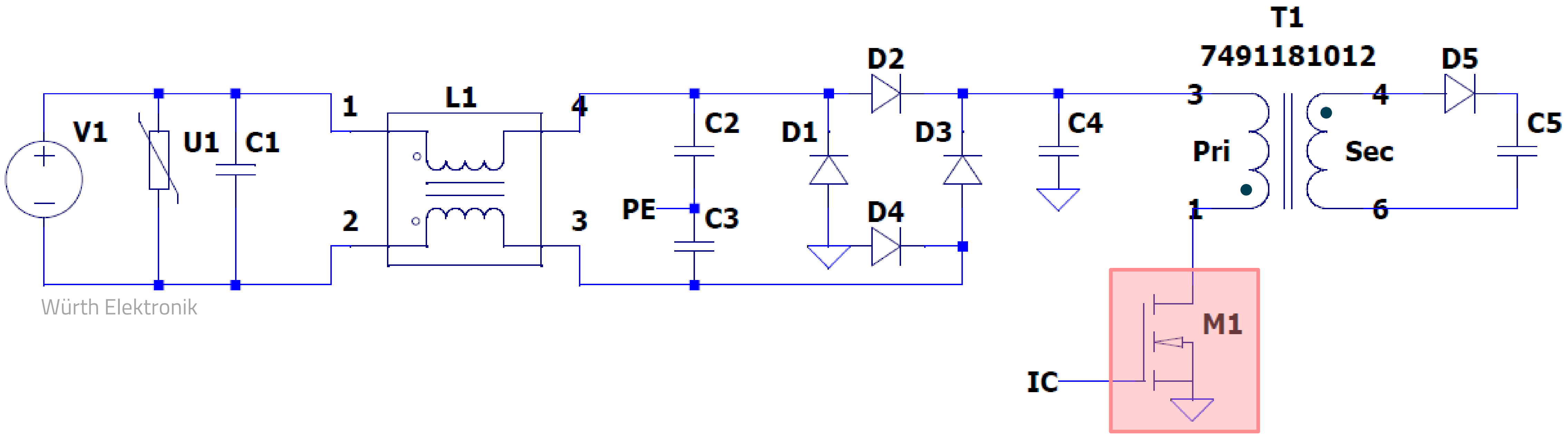

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HIGH VOLTAGE IN MAGNETICS

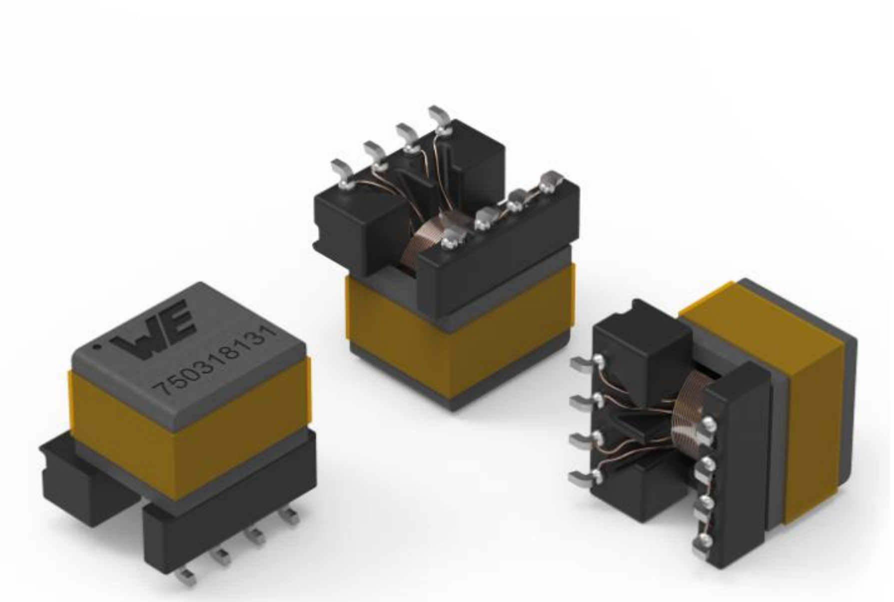
HIGH VOLTAGE IN MAGNETICS

Dielectric Breakdown Failures

- Dielectric breakdown can occur from a few different ways
  - Through the air
  - Over the surface of a material
  - Through a material

- How do magnetics protect against these Dielectric failures?
  - Clearance
  - Creepage
  - Solid insulation, thin sheet insulation, wire insulation

- What tests are done to prove this?
  - Dielectric test
  - Surge test
  - Partial Discharge test



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Voltage Breakdown through Air

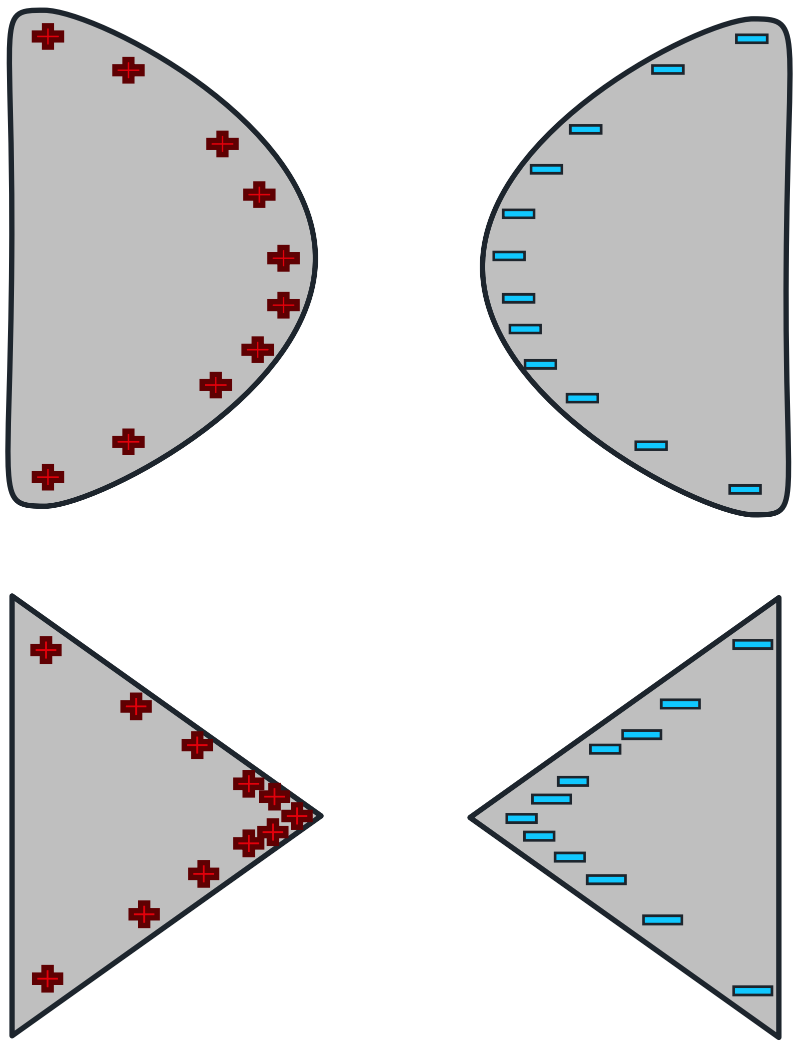
Is the dielectric breakdown through air always the same?

Temperature, humidity, elevation, and more affect the value to breakdown through air

HIGH VOLTAGE IN MAGNETICS

Voltage Breakdown through Air – Shape of Conductor

- The shape of conductors also plays a factor
- Curved surfaces
  - Distribute the charge more evenly
  - This requires them to have a large voltage to have breakdown occur
- Sharp points
  - The charge build up in the tips
  - Due to charge build up, the voltage can create a breakdown at a much lower value



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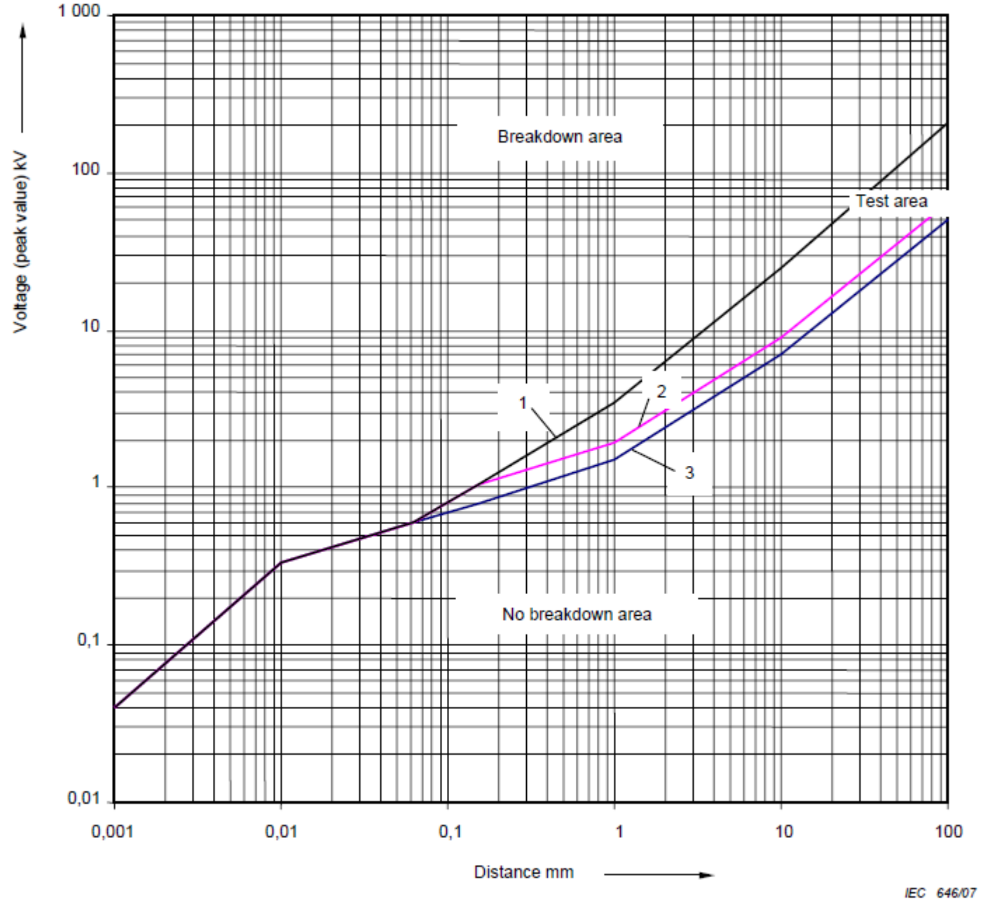
HIGH VOLTAGE IN MAGNETICS

Voltage Breakdown through Air – Shape of conductors

- 60664-1 IEC:2007 has a great graph that shows the breakdown over different E-Fields and distance
- Case B is for a homogeneous field, which would be a curved surface in this case
- Whereas Case A is for an inhomogeneous field, which sharp points would be an example of this



Key

1 case B; $\hat{U}$ 1,2/50 and $\hat{U}$ 50/60 Hz

2 case A; $\hat{U}$ 1,2/50

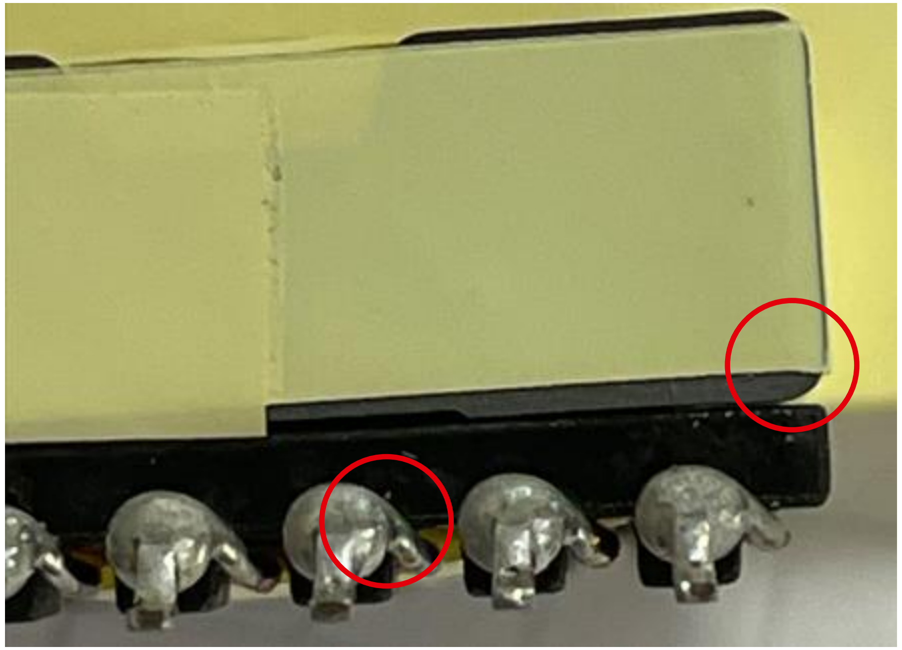
3 case A; $\hat{U}$ 50/60 Hz

Figure A.1 – Withstand voltage at 2 000 m above sea level

HIGH VOLTAGE IN MAGNETICS

Voltage Breakdown through Air - Places to watch in parts

- Real world examples we need to watch
  - Solder spikes
  - Core edges
  - Wire wraps
  - Pin tips



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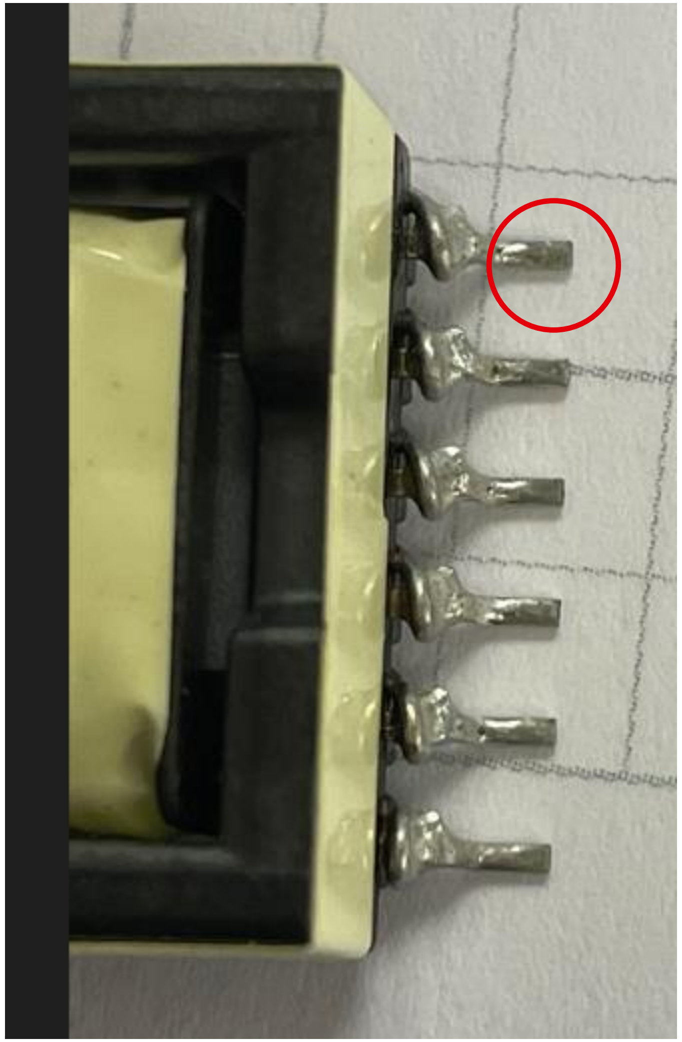

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HIGH VOLTAGE IN MAGNETICS

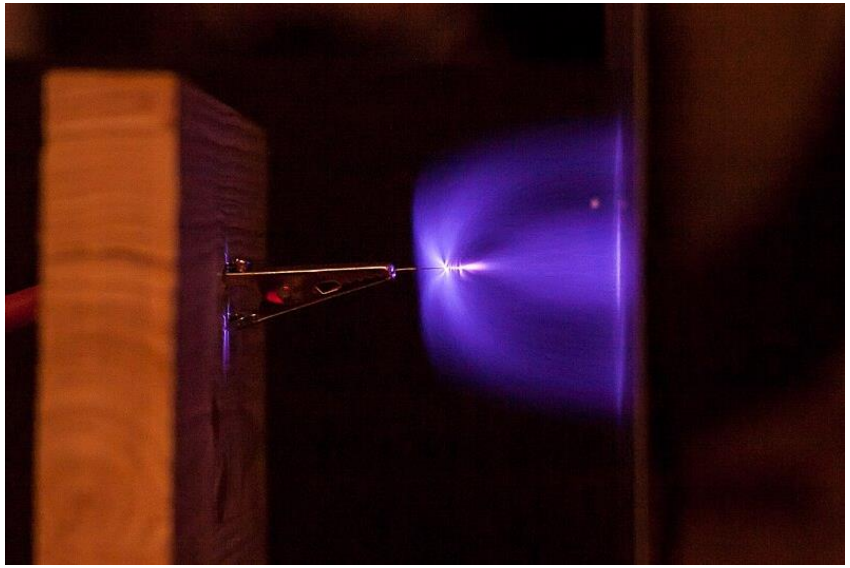
Voltage Breakdown over material - Comparative Tracking Index (CTI)

- Breakdown can also occur across the surface of materials
  - High voltage will start to create an arc that carbonizes the path until a short is created and breakdown occurs
  - Comparative tracking index (CTI) is a method for knowing if an insulating material is more susceptible to tracking
    - Material group 1 (>600V) is highest rating, thus a higher voltage is needed for tracking
    - Material group 3b (<175V) is the lowest

HIGH VOLTAGE IN MAGNETICS

Voltage Breakdown beginning - Corona discharge

- Corona discharge occurs when high voltage starts to ionize the air, which can emit light
- The air has had dielectric breakdown occur and the air is now conductive
- The distance can grow with the air moving
- Can occur in magnetic designs when windings with a large voltage difference are placed close to each other
  - Will start to cause insulation damage until a large failure occurs



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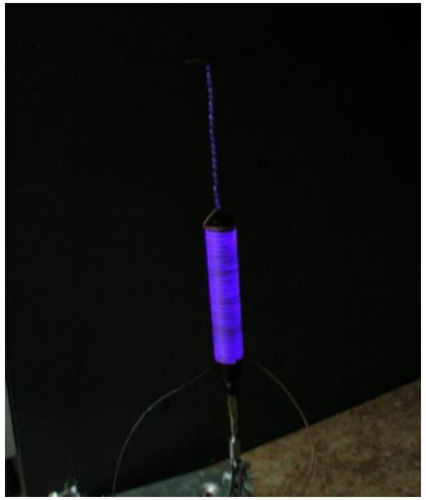

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HIGH VOLTAGE IN MAGNETICS

Magnetics - Safety Distances

- Clearance: Shortest distance thru air between X and Y.
  - Larger distances are needed at higher elevations

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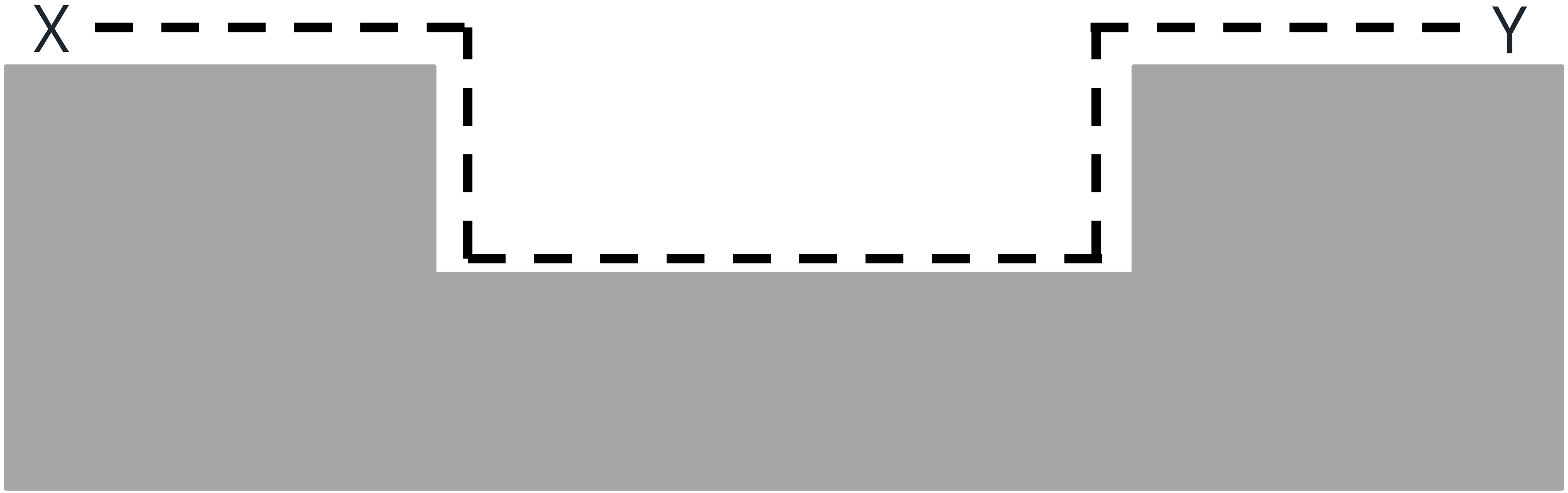
HIGH VOLTAGE IN MAGNETICS

Magnetics - Safety Distances

- Creepage: Follows the material path between X and Y.
  - Minimum gaps are needed by safety standards typically.
  - Group 3 materials will need a larger distance due to CTI.
  - Cannot be smaller than the clearance value



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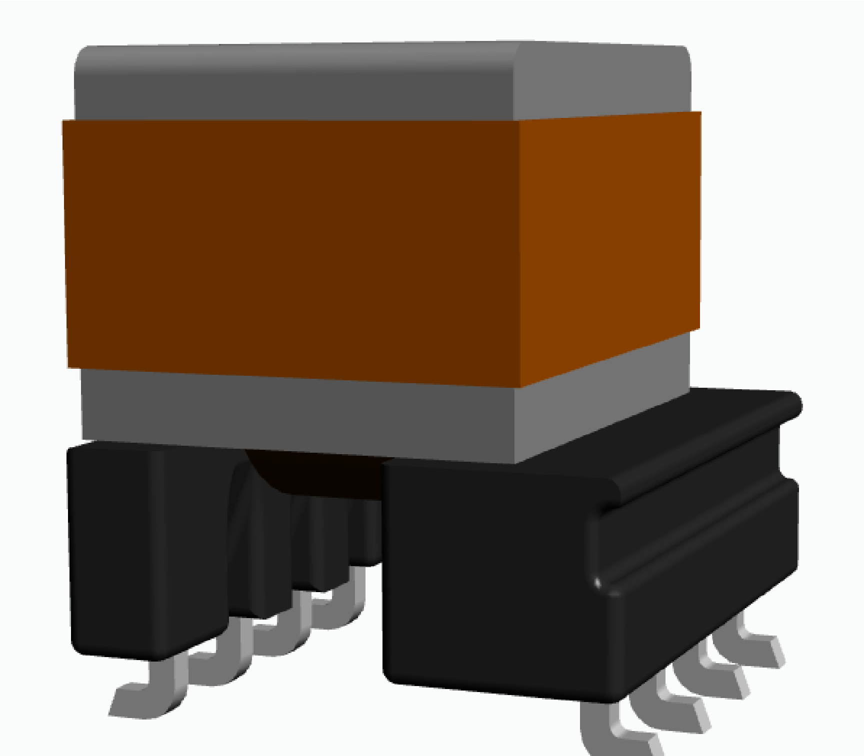
HIGH VOLTAGE IN MAGNETICS

Magnetics - Safety Distances - Examples

Isolated Transformer



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Common Mode Choke

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HIGH VOLTAGE IN MAGNETICS

Magnetics - Safety Distance

- Distance through insulation
  - Conductors can be closer together if an insulative material is used

  - Solid Insulation
    - Material that has no voids
    - Commonly plastics or potting materials

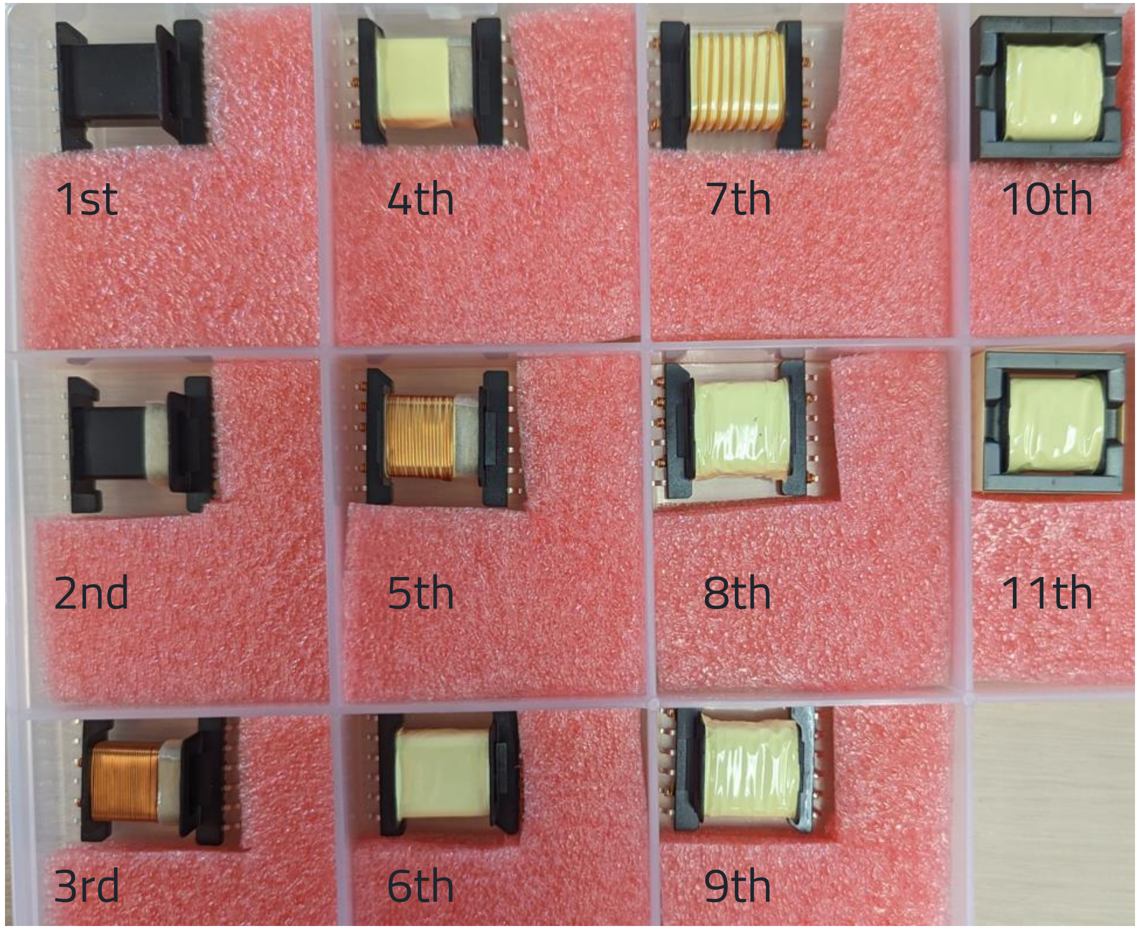
  - Thin sheet insulation
    - Tape can be used to create a thinner insulation
    - Based on the thickness, overlap, and dielectric rating
    - Common to use 2-3 layers for this
      - Electrical Insulation system and higher voltage may require more layers

  - Wire Insulation
    - Magnetwire – Is considered bare wire by safety standards
    - Fully Insulated Wire (FIW) – Similar to magnetwire, but guarantees no defects, may be used for safety
    - Triple Insulated Wire (TIW) – Extruded coating over wire commonly used to meet safety

HIGH VOLTAGE IN MAGNETICS

Magnetics - Safety Distance

- Bobbin – used to form coil and prevent shorts to core
- Margin tape – used to add creepage and clearance
- Wrapper tape – protect winding to winding
- Crossover tape –prevents two wires crossing (insulation cut through)



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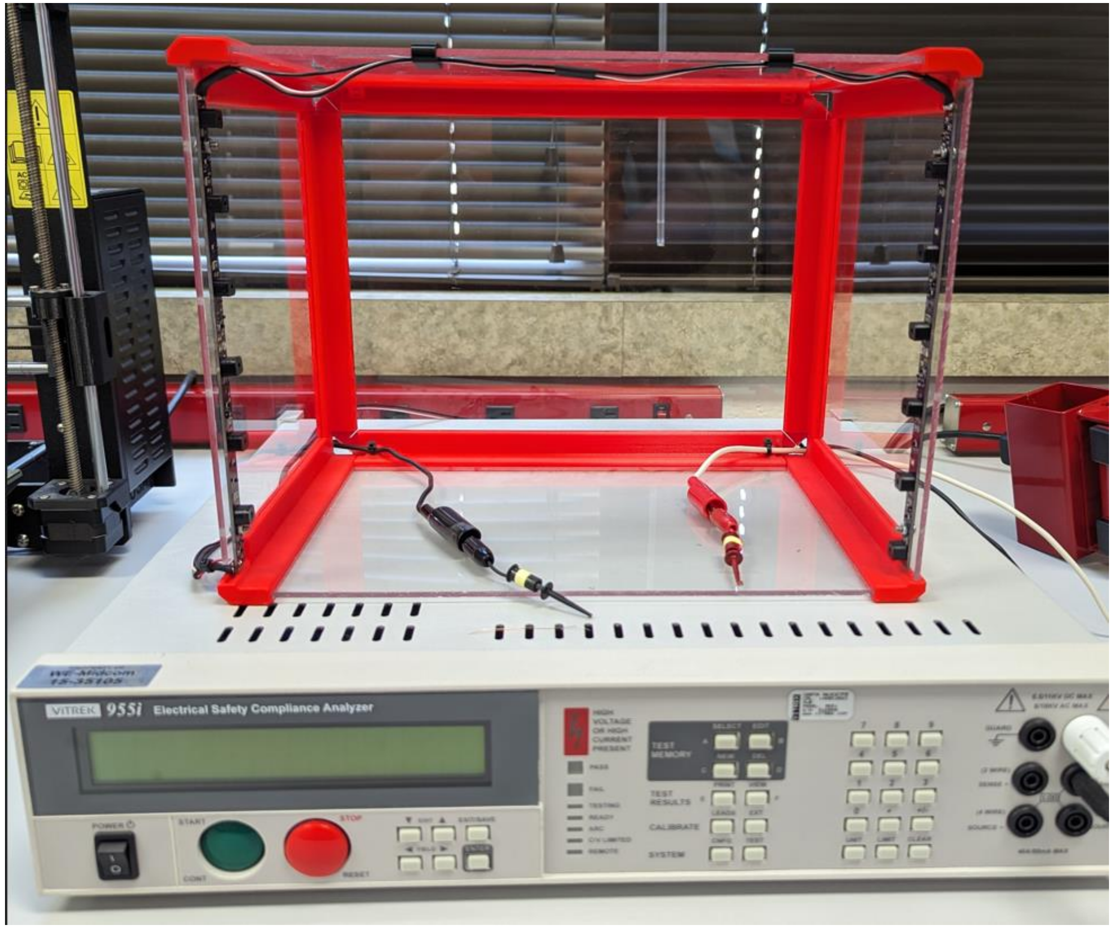
HIGH VOLTAGE IN MAGNETICS

Magnetics - Testing

- Dielectric testing
  - Is applying voltage across the insulation barrier of the part.
  - Typically is a 60 second test on samples and 1-5 second test in production
  - Can be an AC (50/60Hz) or DC voltage that is applied
  - The leakage current is then set to 500 µA limit

- Surge testing
  - Fast rise in voltage that is meant to act like an indirect lighting strike, fault, or quick load change
  - 1.2 /50 µseconds waveform is a very typical one for industrial
    - 1.2 µseconds rise from 10% voltage to 90% voltage
    - At 50 µseconds still at least 50% voltage



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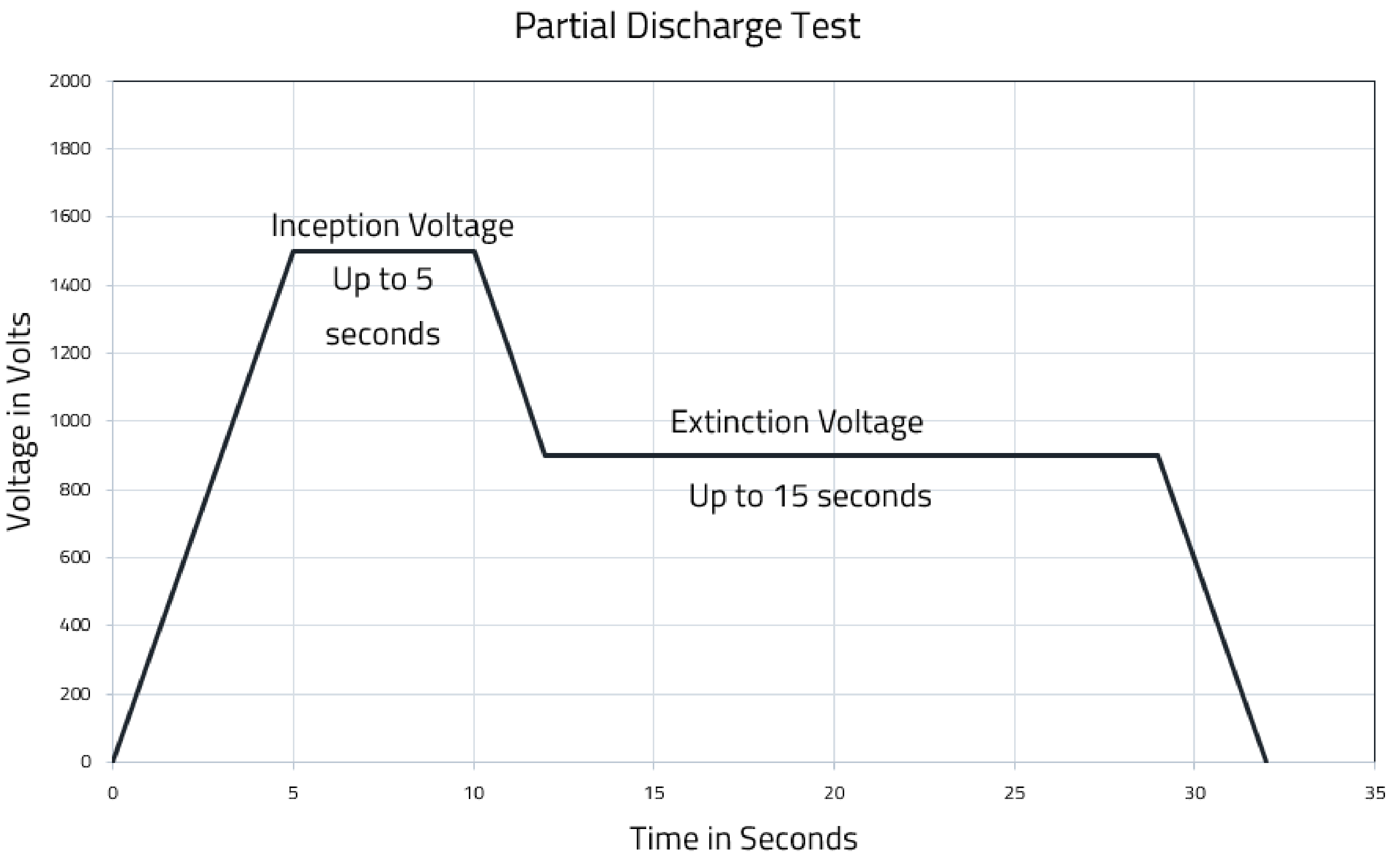
HIGH VOLTAGE IN MAGNETICS

Magnetics - Testing

- Partial Discharge testing
  - Test looks for small discharges in voids, cracks, or damage to the insulation
  - Part fails if 10pC is exceeded during extinction voltage
  - Okay to exceed during inception voltage
  - Charge = Current x Time
  - 1pC = 1μA x 1μSecond



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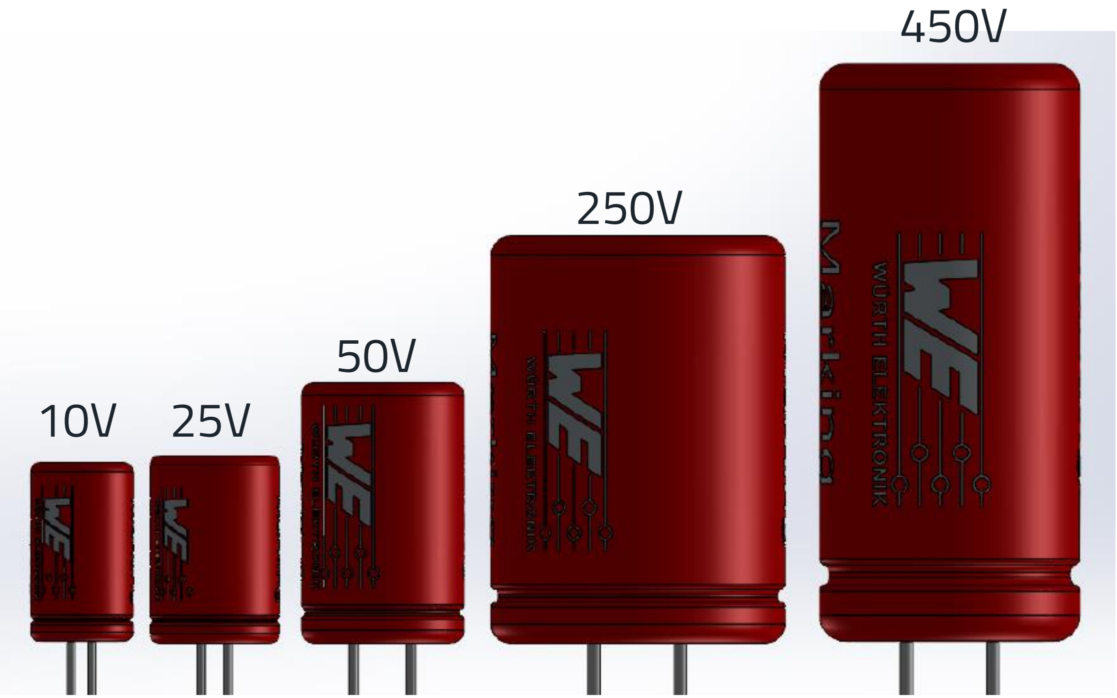
HIGH VOLTAGE IN CAPACITORS

HIGH VOLTAGE IN CAPACITORS

Aluminum Electrolytic Capacitor Challenges

- As rated voltage in an electrolytic capacitor increases, so does the height
- If rated voltage is exceeded, capacitors top will pop at the relief vent lines
- Is there a way to get higher rated voltage without the extra height?

100µF Capacitors



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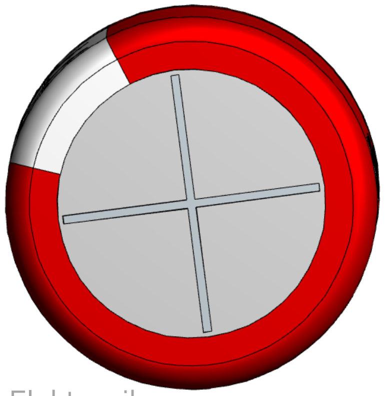

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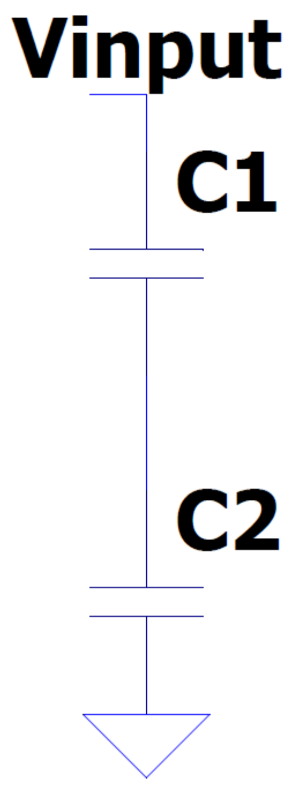
HIGH VOLTAGE IN CAPACITORS

Aluminum Electrolytic Capacitor Stacking

- One option is to stack in series the Electrolytic Capacitors
  - The rated voltage will add together
  - Overall capacitance will be halved (if same value) since in series

- Is this always a safe option to do?
  - If overall voltage rating of Caps is far away from system voltage
    - Capacitors in series are okay
  - If overall voltage rating of Caps is close to system voltage
    - Additional balancing is needed, which can be done with resistors
    - Differences in leakage current from part to part or drift over time can cause failures



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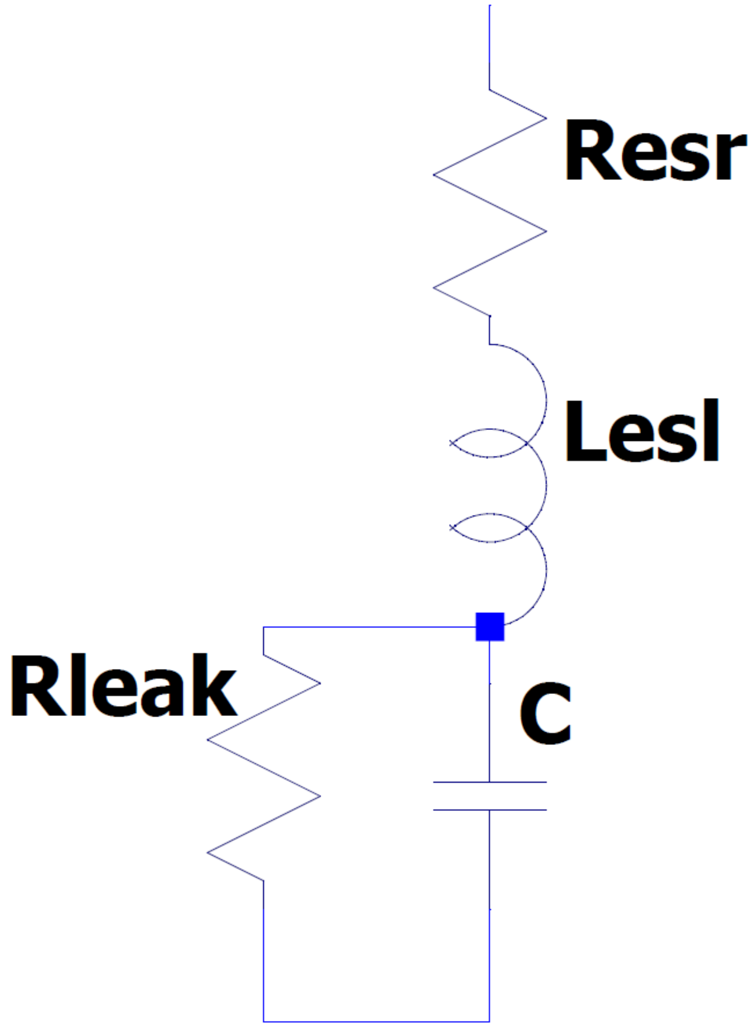
HIGH VOLTAGE IN CAPACITORS

Capacitor Balancing LTspice

- Equivalent circuit of a Capacitor has
  - Capacitance
  - Equivalent Series Resistance (ESR)
    - Used for losses
    - How quickly it charge/discharge
  - Equivalent Series Inductance (ESL)
    - Due to the leads and connections to PCB
  - Parallel Resistance
    - Added to model to take into consideration leakage current



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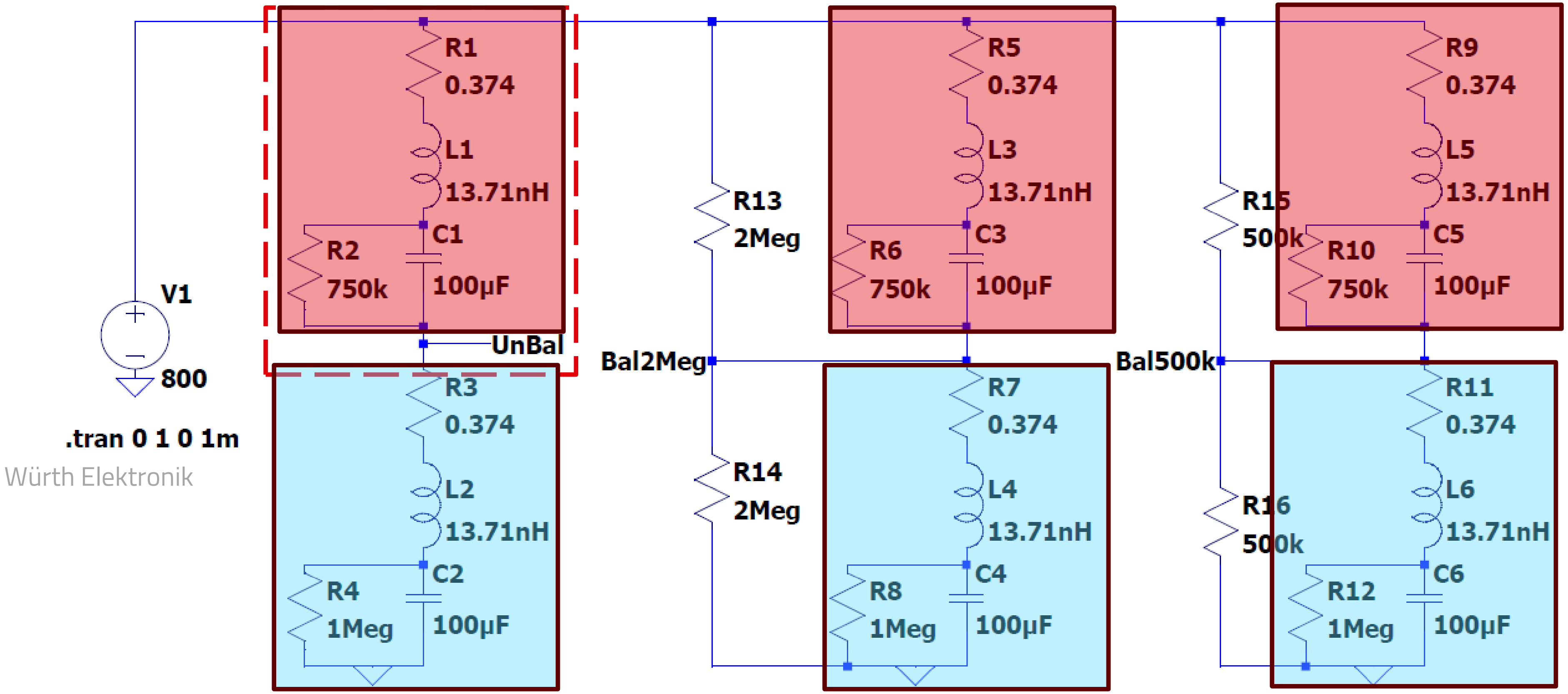
HIGH VOLTAGE IN CAPACITORS

Capacitor Balancing LTspice

- Simulation shows an unbalanced system and two different balanced system when 800VDC is applied
- Uses equivalent circuit model of 860241480001 (100µF 450V Capacitor) on bottom and higher leakage version on top



HIGH VOLTAGE IN CAPACITORS

Capacitor Balancing LTspice

	Voltage between Capacitors	Power loss from Resistors
Unbalanced Capacitors	457V	NA
2MOhm Balanced Capacitors	440V	162mW
500kOhm Balanced Capacitors	421V	642mW

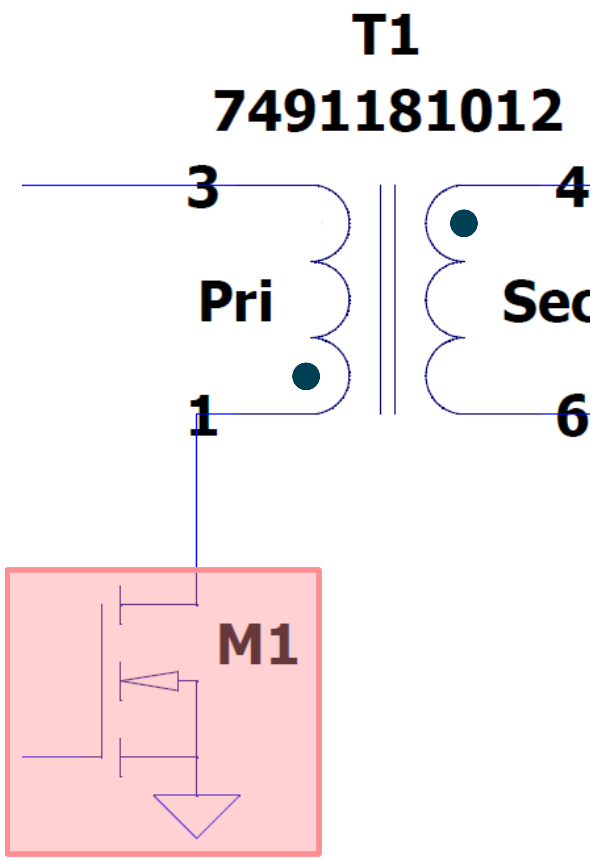
- Initial DC voltage was at 800V
- Unbalanced capacitors could fail in time due to exceeded voltage
- Lower resistance balances better, but at a cost

HIGH VOLTAGE IN TRANSISTORS

HIGH VOLTAGE IN TRANSISTORS

Transistor breakdown voltage

- Breakdown can occur when Drain to Source Voltage rating is exceeded.
  - Two voltages to watch out for
    - Reflected voltage from Transformer
    - Ringing voltage on the Drain of Transistor



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HIGH VOLTAGE IN TRANSISTORS

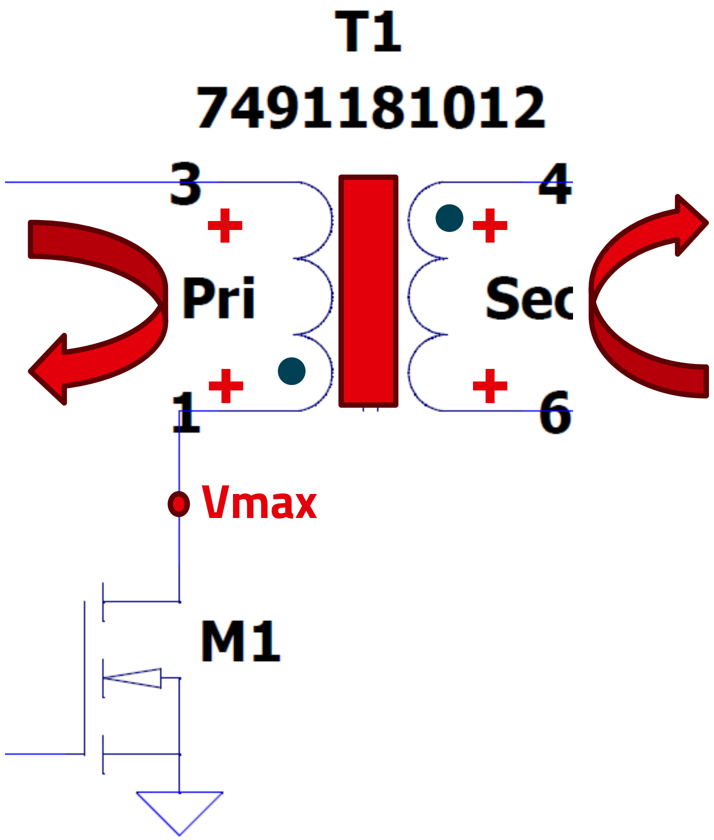
Reflected Voltage from Transformer

- Flyback Transformers are a coupled inductor
  - Energy is built up in Magnetic Field (gap of core)
  - Then released on the secondary side

- When Secondary takes energy
  - Reflected voltage add based on turns ratio

- Initial selection use transistor with 2x Vds breakdown of input voltage
  - Tighter selection can be made, but close attention to turns ratio needed

$$Vmax = Vin + (Vout + Vdiode) * \frac{Np}{Ns}$$

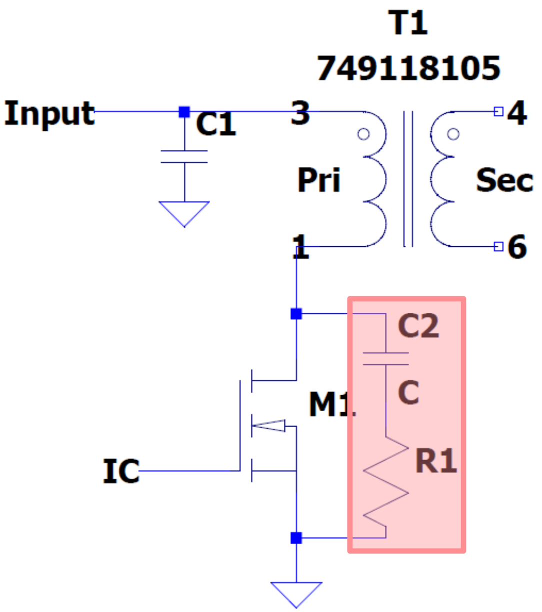


HIGH VOLTAGE IN TRANSISTORS

Ringing Voltage on Drain Node

- Ringing will also occur on the drain of transistor
  - Caused by leakage inductance of transformer and drain to source capacitance of transistor
  - Voltage can easily swing to high due to resonance

- Snubbers can be used to clamp or minimize these spikes
  - RC Snubber across transistor
    - Calculated based on frequency of oscillations
    - Needs to be adjusted once circuit is built
  - RCD Snubber across primary of transformer
    - Diode helps to clamp voltage to a set point



RC Snubber
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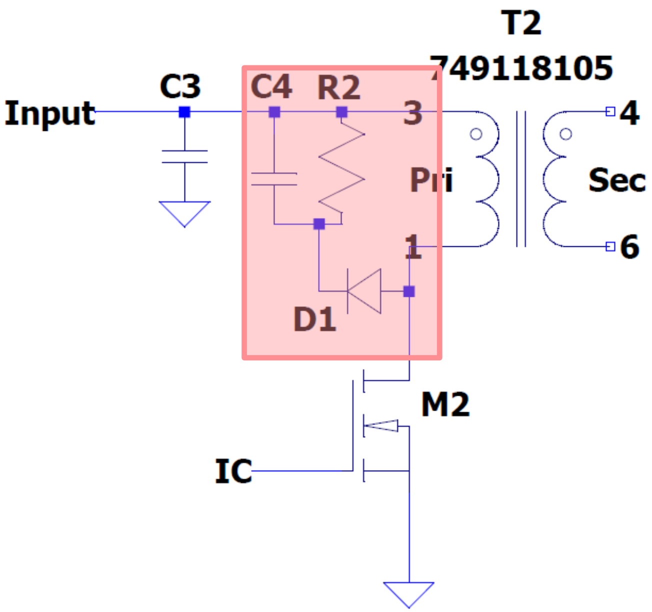

RCD Snubber
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HIGH VOLTAGE IN TRANSISTORS

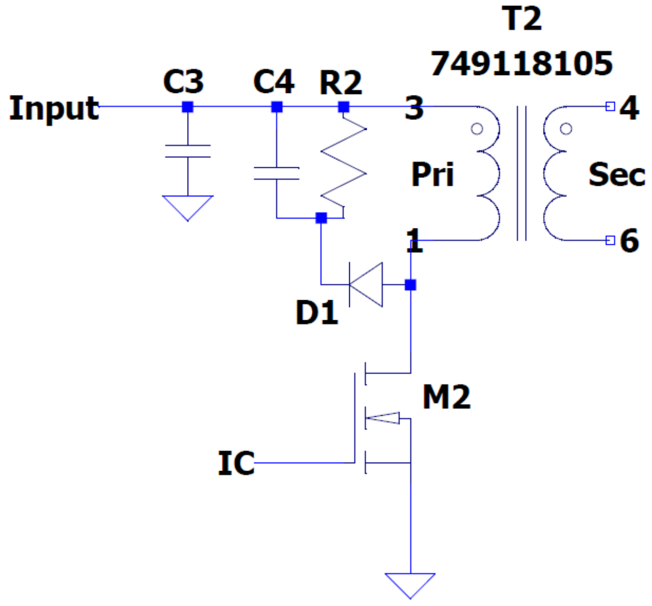
Calculations and Considerations for RCD Snubber

- Capacitor is used to absorb energy from Leakage Inductance
- Diode placed so snubber only works in off time

- First, we estimate the snubber voltage
  - K is just a constant of 1.5 to 2.5
  - $Vsnub = k * (Vout + Vdiode) * \frac{Np}{Ns}$

- Next, we calculate Capacitor needed based on the energy
  - $\frac{1}{2} * (Lleak) * (Ipeak)^2 = \frac{1}{2} * Csnub * (Vsnub)^2$

- Rewriting this we get the equation below
  - $Csnub = \frac{(Lleak)*(Ipeak)^2}{(Vsnub)^2}$



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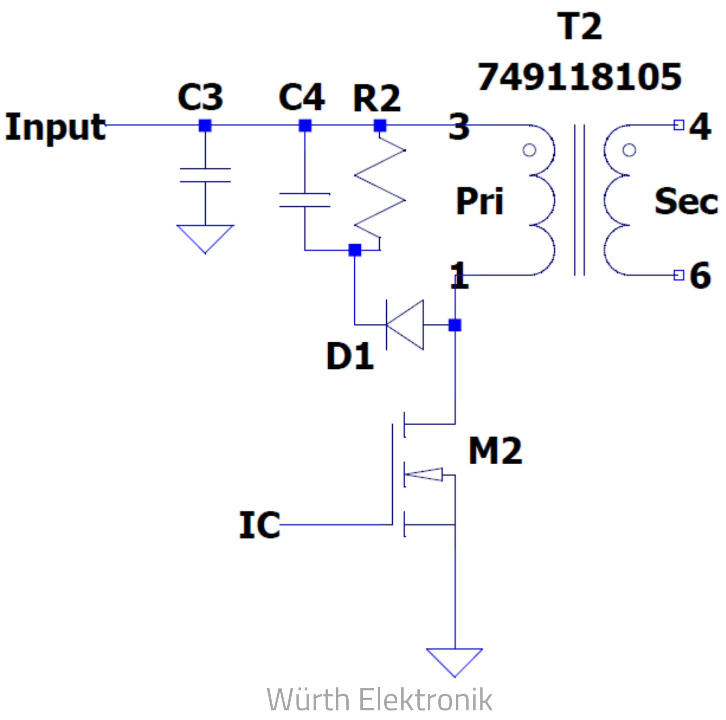
HIGH VOLTAGE IN TRANSISTORS

Calculations and Considerations for RCD Snubber

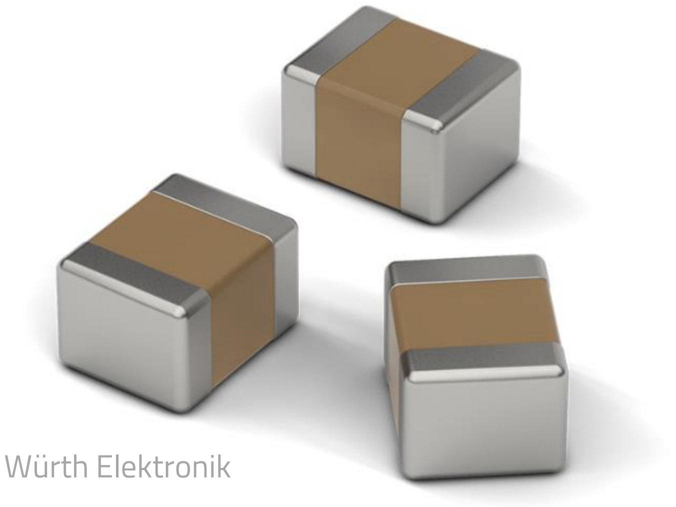
- Next to calculate the resistor
  - Use 1/3 RC time constant to dissipate 95% of energy
  - $Rsnub = \frac{\frac{1}{3} * (Ton\ min)}{Csnub}$
- Calculate Power for resistor
  - $P = \frac{0.5 * Csnub * (Vsnub)^2}{(Ton\ min)}$
- These equations are used for a starting point and adjustments during the prototyping stage are likely



HIGH VOLTAGE IN TRANSISTORS

RCD Snubber Selection Parameters

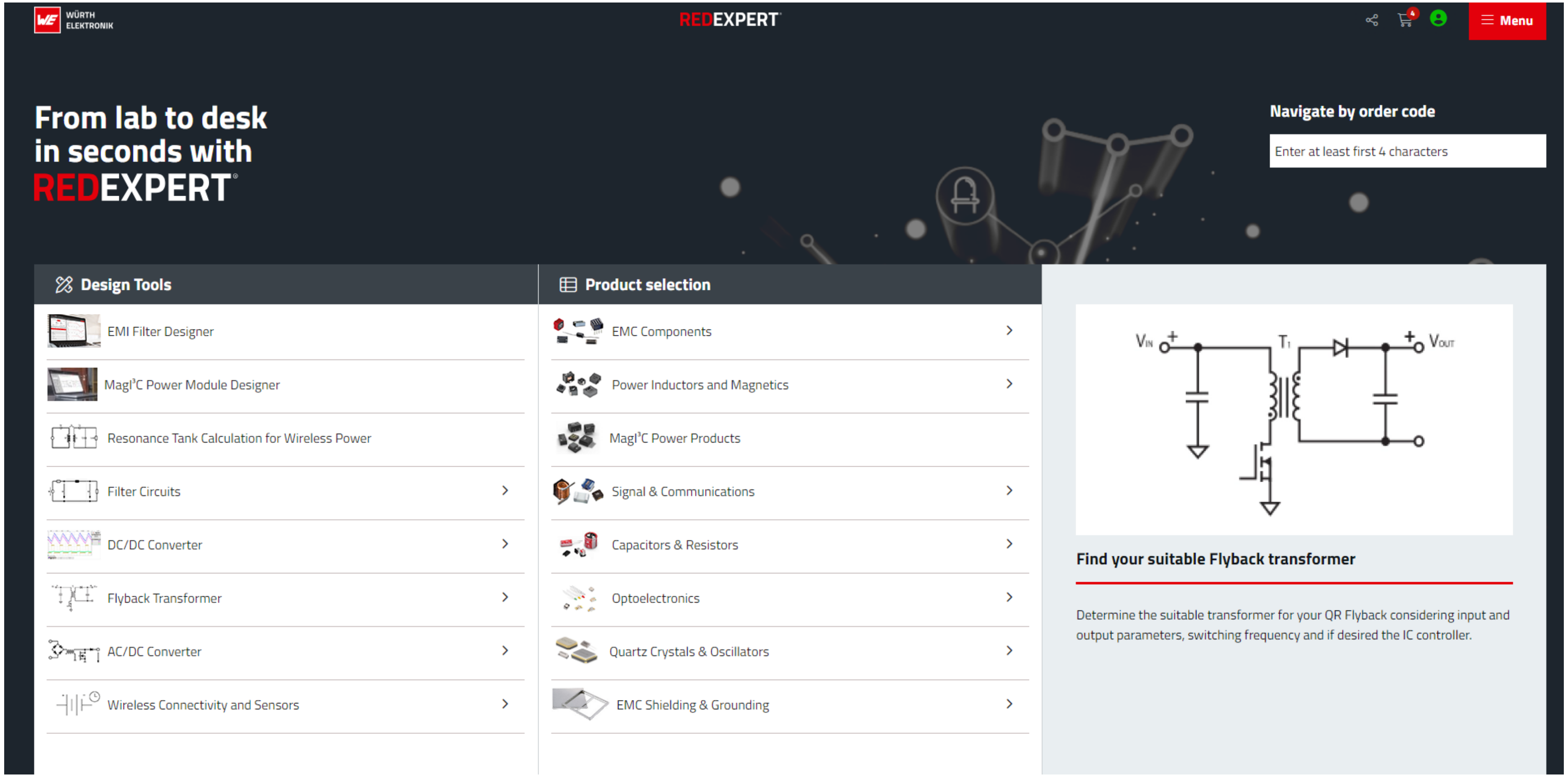
- Resistor
  - Resistance value
  - Power rating
  - Voltage rating
- Capacitor
  - Capacitance value
  - Voltage rating
  - Recommend Class 1 MLCC (NP0)
    - No DC bias to capacitance
- Diode
  - Voltage rating
  - Fast reverse recovery
  - Recommend Schottky or Ultra-Fast



HELPFUL TOOLS

REDEXPERT

Link to REDEXPERT



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REDEXPERT

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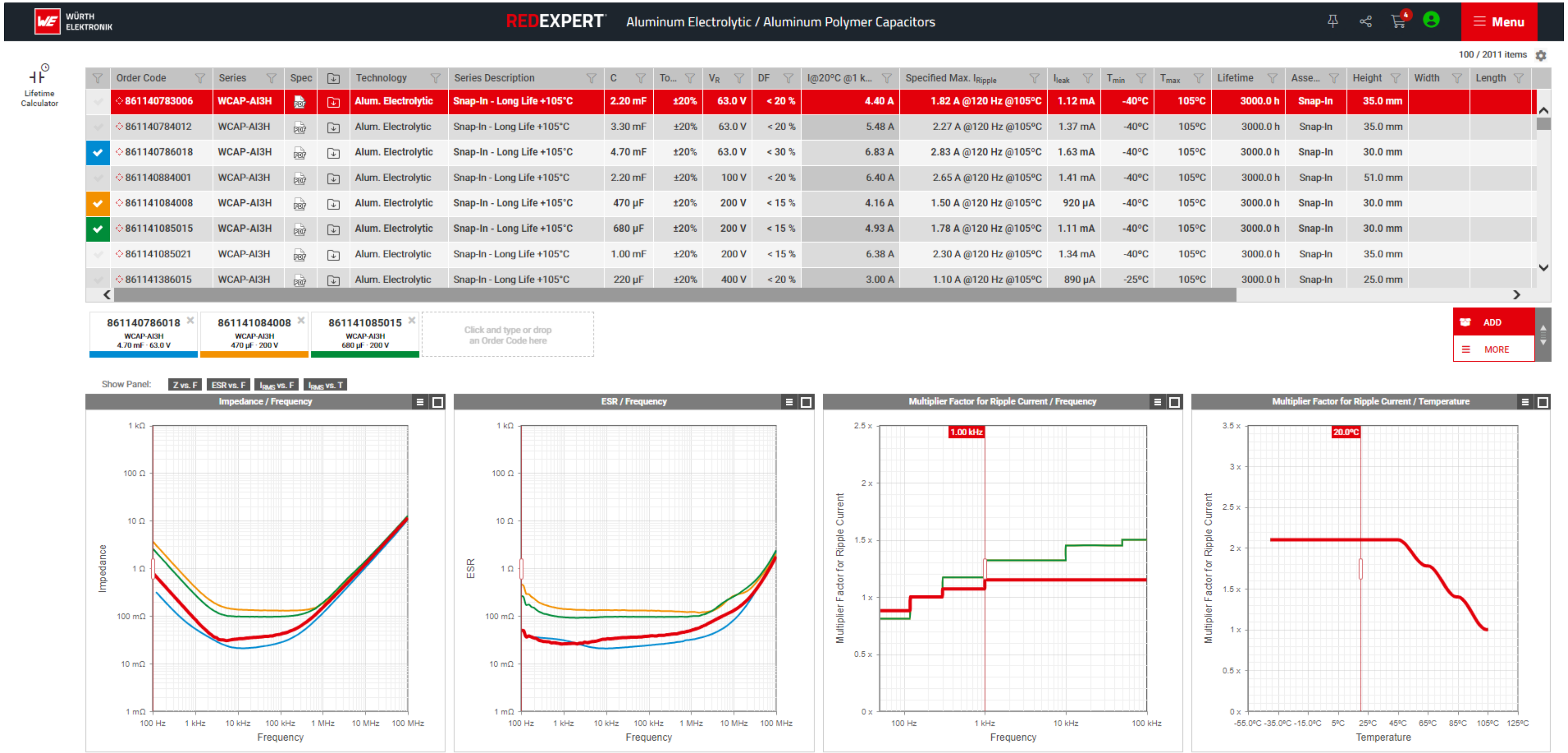

Order Code	Series	Technology	Series Description	C	To...	V_R	DF	I@20°C @1 k...	Specified Max. I_{Ripple}	I_{leak}	T_{min}	T_{max}	Lifetime	Asse...	Height	Width	Length
861140783006	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	2.20 mF	±20%	63.0 V	< 20 %	4.40 A	1.82 A @120 Hz @105°C	1.12 mA	-40°C	105°C	3000.0 h	Snap-In	35.0 mm		
861140784012	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	3.30 mF	±20%	63.0 V	< 20 %	5.48 A	2.27 A @120 Hz @105°C	1.37 mA	-40°C	105°C	3000.0 h	Snap-In	35.0 mm		
861140786018	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	4.70 mF	±20%	63.0 V	< 30 %	6.83 A	2.83 A @120 Hz @105°C	1.63 mA	-40°C	105°C	3000.0 h	Snap-In	30.0 mm		
861140884001	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	2.20 mF	±20%	100 V	< 20 %	6.40 A	2.65 A @120 Hz @105°C	1.41 mA	-40°C	105°C	3000.0 h	Snap-In	51.0 mm		
861141084008	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	470 µF	±20%	200 V	< 15 %	4.16 A	1.50 A @120 Hz @105°C	920 µA	-40°C	105°C	3000.0 h	Snap-In	30.0 mm		
861141085015	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	680 µF	±20%	200 V	< 15 %	4.93 A	1.78 A @120 Hz @105°C	1.11 mA	-40°C	105°C	3000.0 h	Snap-In	30.0 mm		
861141085021	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	1.00 mF	±20%	200 V	< 15 %	6.38 A	2.30 A @120 Hz @105°C	1.34 mA	-40°C	105°C	3000.0 h	Snap-In	35.0 mm		
861141386015	WCAP-AI3H	Alum. Electrolytic	Snap-In - Long Life +105°C	220 µF	±20%	400 V	< 20 %	3.00 A	1.10 A @120 Hz @105°C	890 µA	-25°C	105°C	3000.0 h	Snap-In	25.0 mm		

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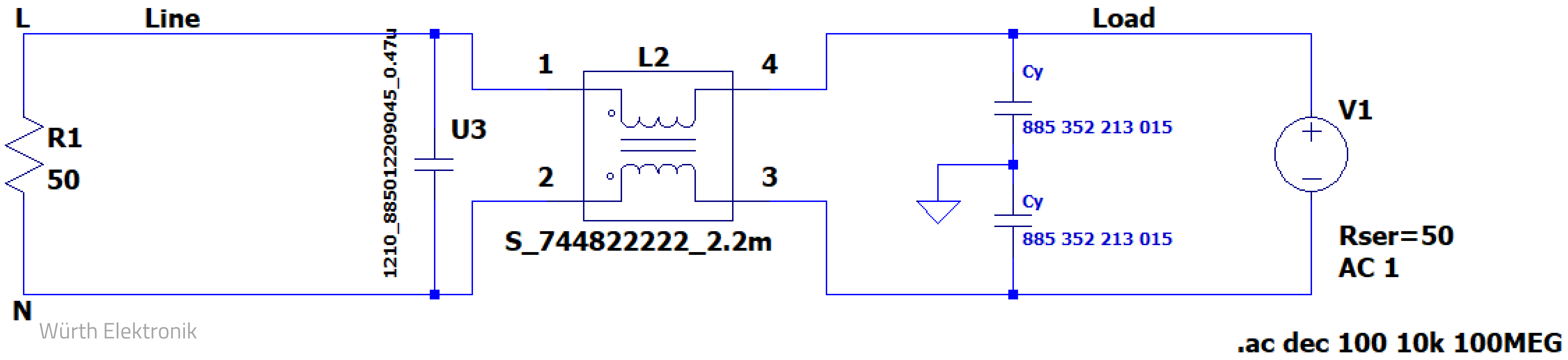
WURTH IN LT SPICE

- Models found in the "Contrib" folder in LTspice.
- Latest updates automatically downloaded when LTspice is updated.
- Use equivalent circuits of real components.
- Do not use to simulate saturation! (Since models do not include accurate nonlinear BH loop



NEED DESIGN HELP?

- 7 different textbooks (magnetics, Ltspice, etc.) Nearly 1000 pages of practical information.
- Over 110 application notes
- Local assistance (email, phone, video call, online chat, etc.)
- Design for Electromagnetic Compatibility--In a Nutshell: Theory and Practice | SpringerLink

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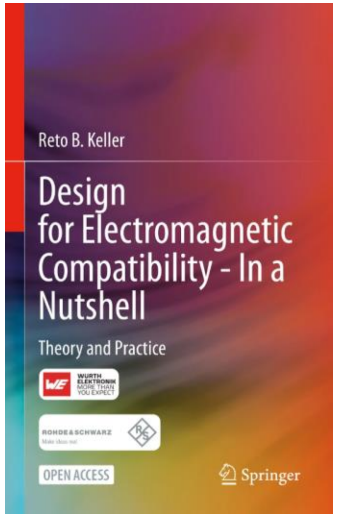

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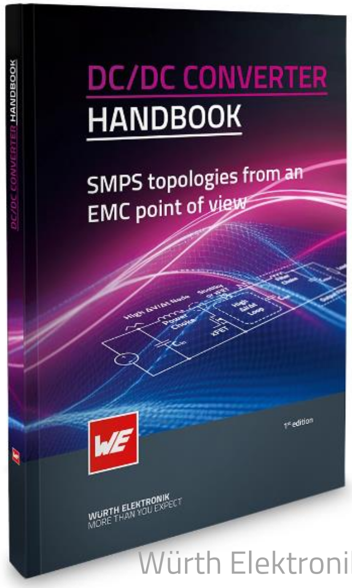

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CONCLUSION

CONCLUSION

- Special Considerations for 480-600VAC inputs
  - Proper magnetics selection
    - Correct safety distances and requirements
  - Balancing of bulk capacitors
  - Selection criteria for transistors
    - Ways to protect transistors from oscillations