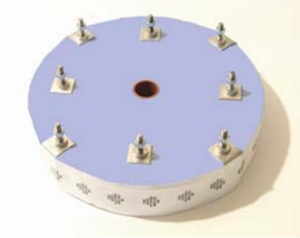

Motor & Drive Systems 2006

Miami, Florida – February 15-16, 2006

Ring Form Factor Film Capacitors for Embedded Motor Controls

Consider an E-Drive Inverter located within the Motor Housing

Presented by:

Terry Hosking, VP of Engineering

SBE, Inc.

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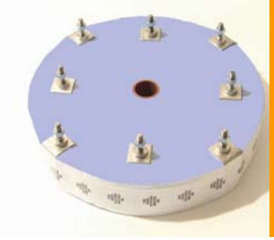

Consider E-Drive Inverter located within the Motor Housing

- Advantages:
  - A more ideal Motor Form Factor for many applications
  - Smaller Volume/Lower Weight System
    - Higher Power Density
  - Electrical Efficiency Improvement Opportunity
  - The possibility to Reduce EMI

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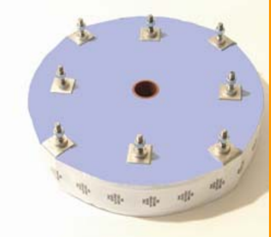
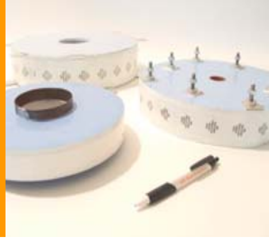


Consider E-Drive Inverter located within the Motor Housing



- Challenges:
  - Thermal Management
    - More Cooling Capacity Needed
  - Sourcing Suitable Components
  - Round PC Boards/Bus Structures are not “the norm”
  - DC Link Capacitor Assembly

Note: The concept of an embedded inverter is not presented as a unique idea

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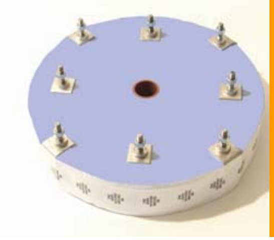

Consider Making the DC Link Capacitor Round

- SBE presents a discussion of DC Link Capacitor-related issues, and a solution to the need for a Round Capacitor.

- The SBE Power Ring™ Solution:
  - Customized Center Hole and Terminal Configuration
  - Highest Capacitance Density
  - Lowest Possible Losses and Inductance
    - Higher Ripple Current Rating

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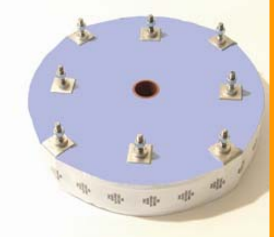
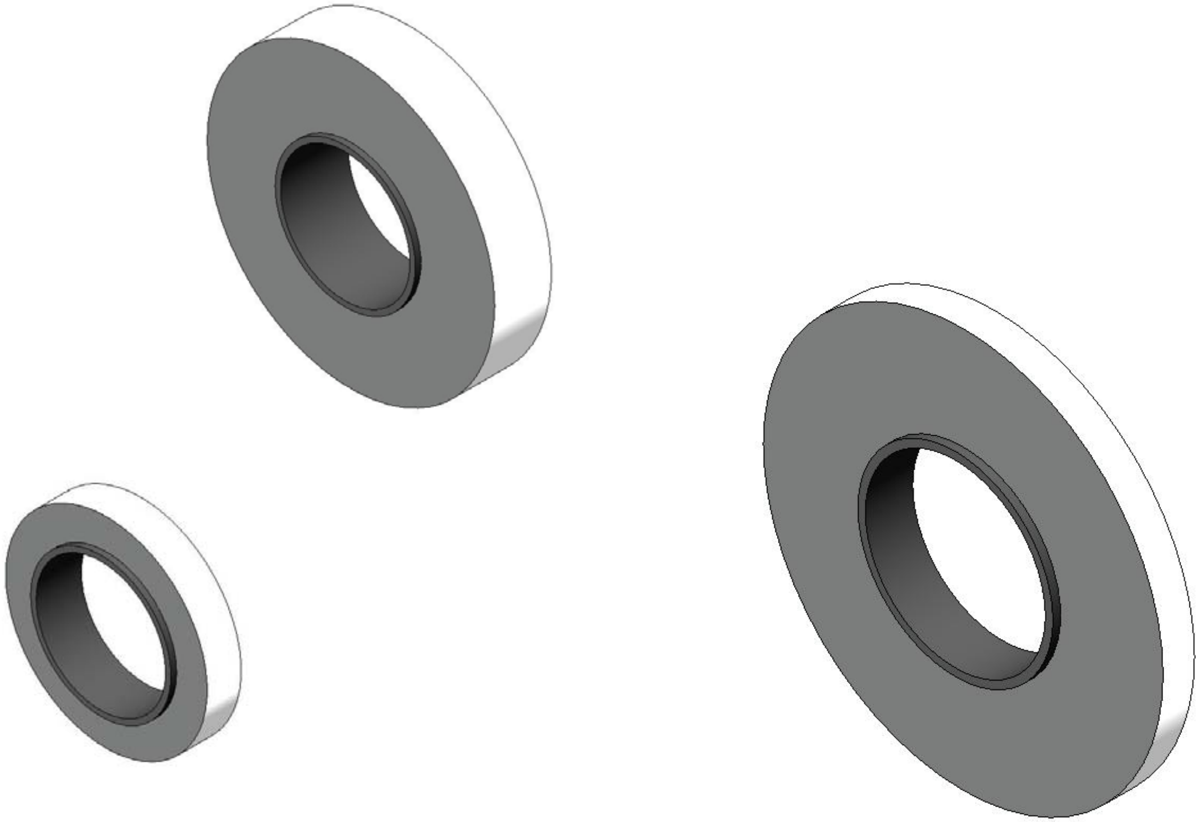


Examples of Ring Form Factor Film Capacitors



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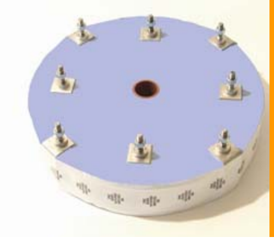
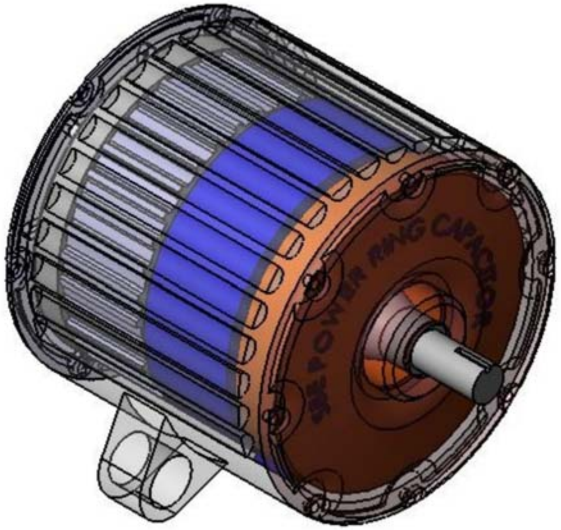


Trade-Off Between Capacitance and Center Hole Size

- The presence of the Center Hole:
  - Can be very useful
  - Results in minimal reduction in capacitance
    - A 30% diameter hole sacrifices less than 10% of the total available ring capacitance



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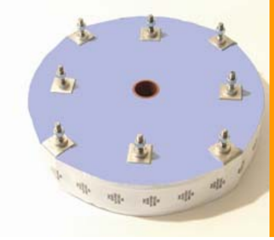

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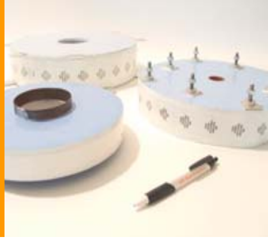

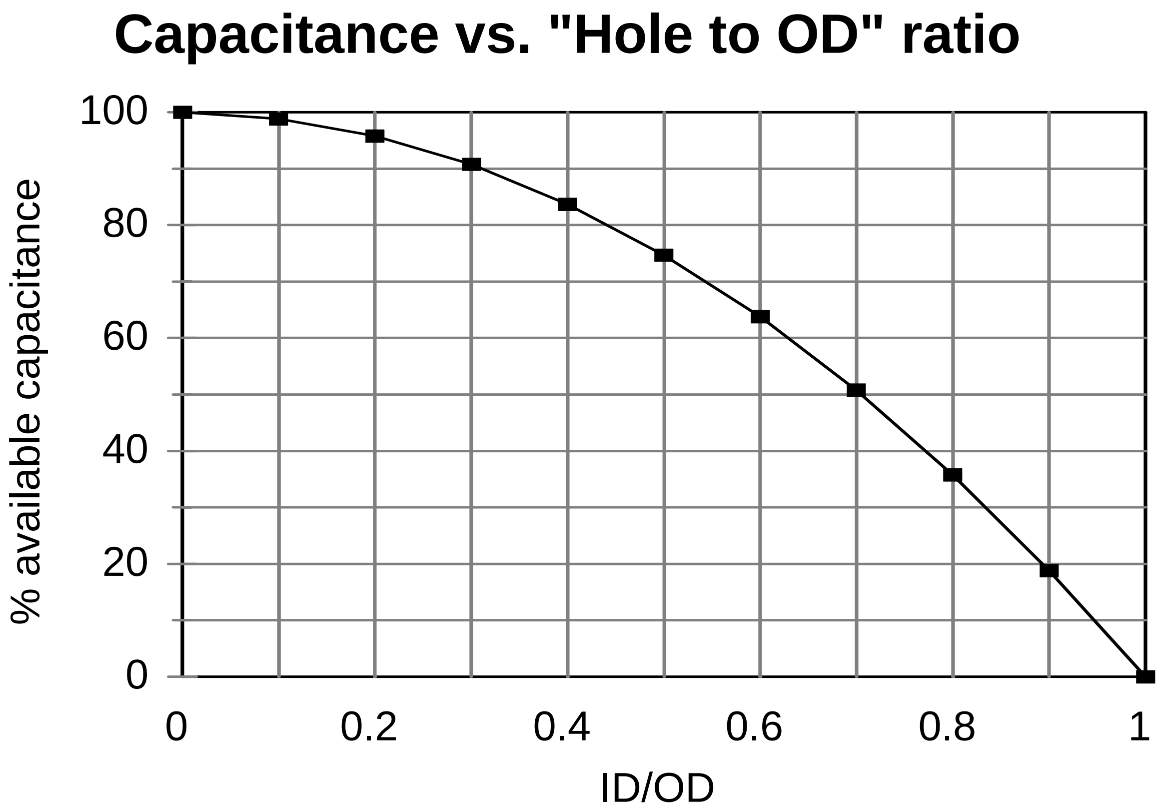

The Hole Subtracts a small percentage of Capacitance

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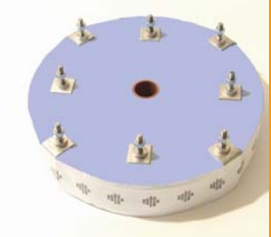
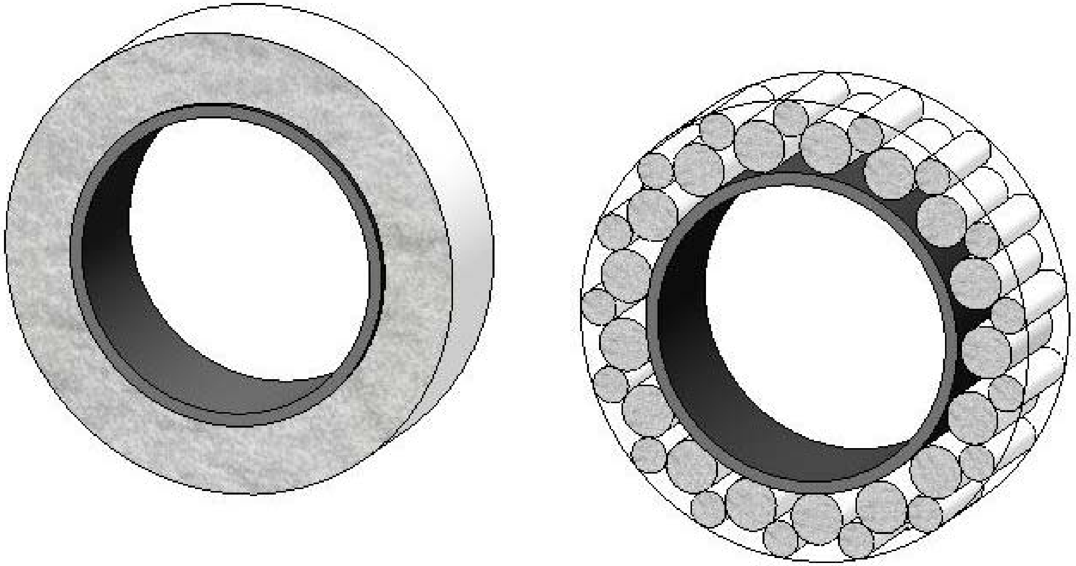


Other Approaches to a Round DC Link Capacitor Implementation

- Others have implemented this concept using discrete capacitor windings



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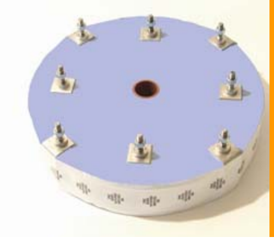
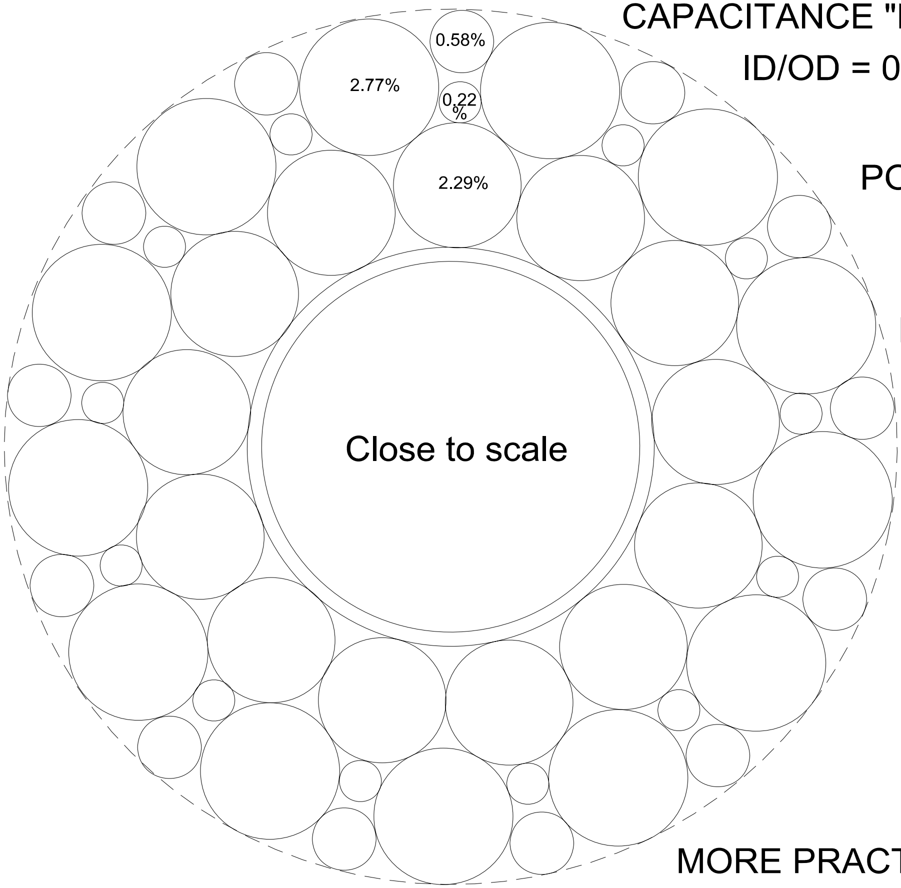


What is the Difference between the Discrete Implementation and the Solid Ring Approach?



CAPACITANCE "PACKING FACTOR"

ID/OD = 0.47 for this example.

POWER RING: 100%

EXTREME PARALLEL DISCRETE SOLUTION:

2.77% * 13 = 36%
2.29% * 13 = 30%
0.58% * 13 = 8%
0.22% * 13 = 3%
TOTAL 77%

MORE PRACTICAL SOLUTION: 66%

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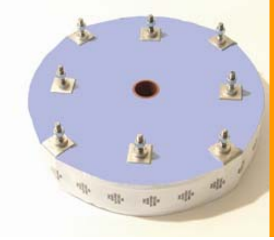

Available Capacitance of the Power Ring?

Consider some Capacitor Sizes Relevant to Typical Electric Motors

- 4.5 inch ID/7 inch OD
- 4.5 inch ID/10 inch OD
- 5.5 inch ID/15 inch OD

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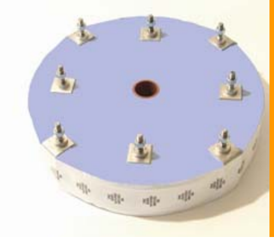
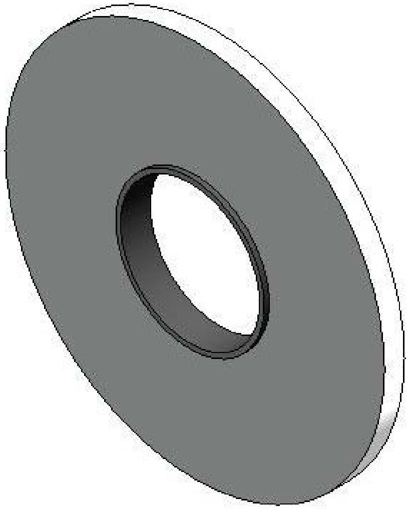
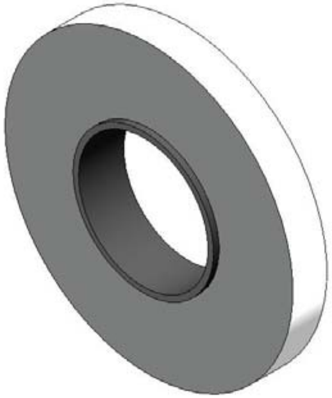


Available Capacitance of the Power Ring?

4.5 inch ID/7 inch OD



5.5 inch ID/15 inch OD



4.5 inch ID/10 inch OD

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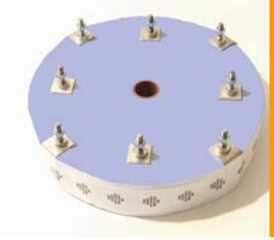
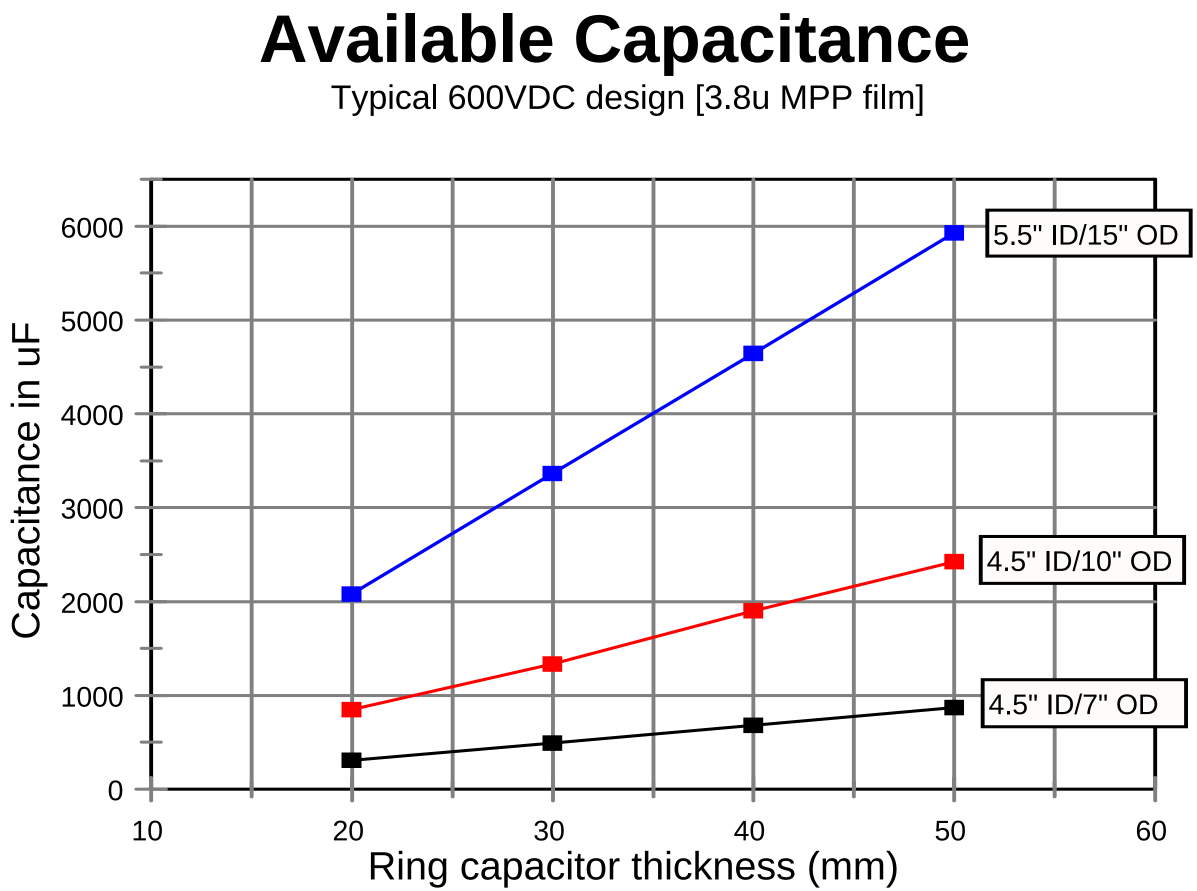


Available Capacitance of the Power Ring



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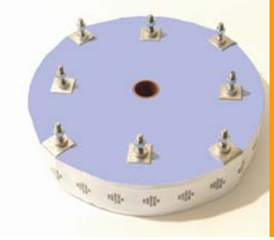

Available Capacitance of the Power Ring

- Graph represents a Nominally Aggressive Capacitor Design
- Increased Dielectric Stress would allow for more capacitance per volume
- But Capacitance change versus thickness will stay the same

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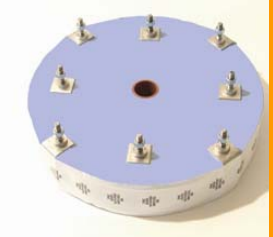
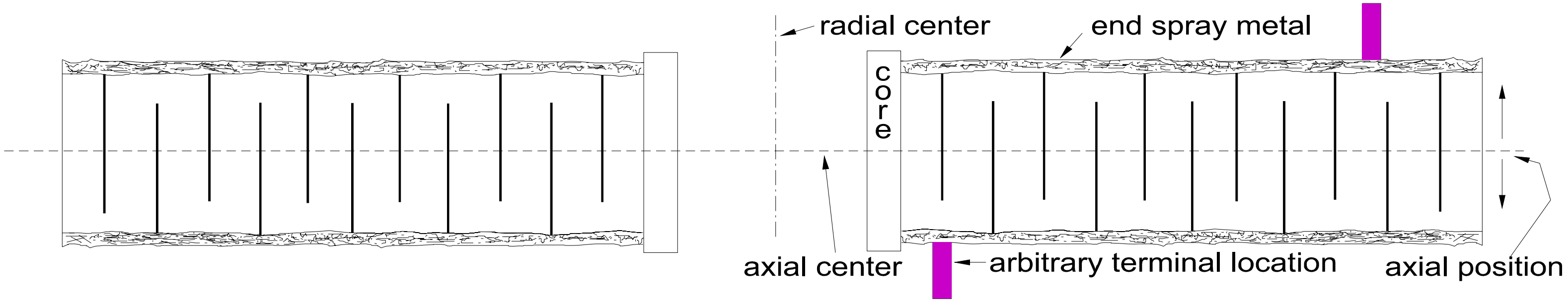


Ring Capacitor Terms



The Large Ring Capacitor behaves as a distributed Circuit Element both Thermally and Electrically

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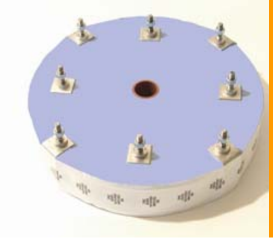
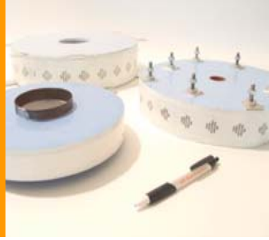
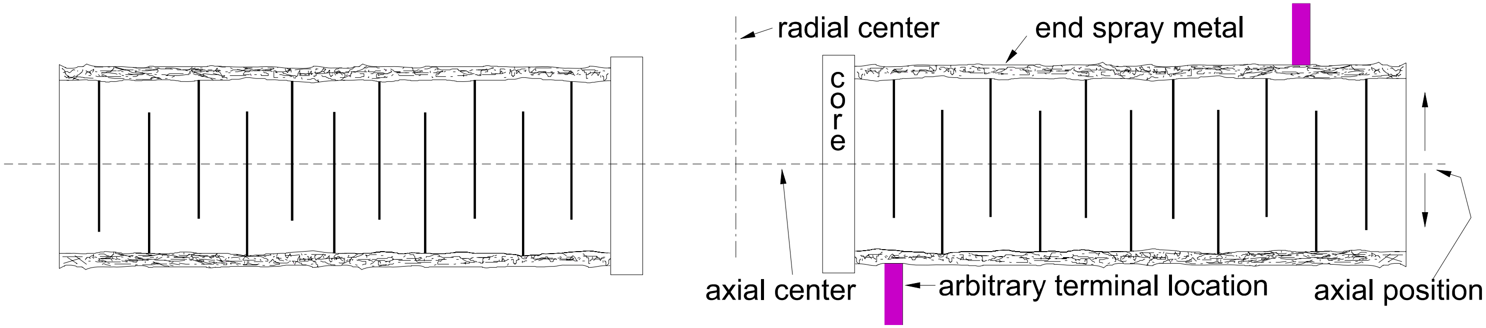


Effects of Increasing Capacitor Thickness



- Increased Electrode Contribution to Total Effective Series Resistance (ESR)
- Increased Series Inductance
- Longer Thermal Path for heat Removal
  - Higher Temperature Rise for a given Dissipation
- Capacitor Hot Spot limits overall System Temperature



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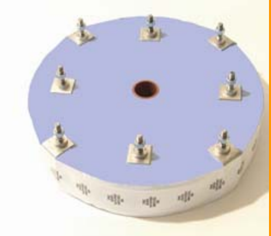

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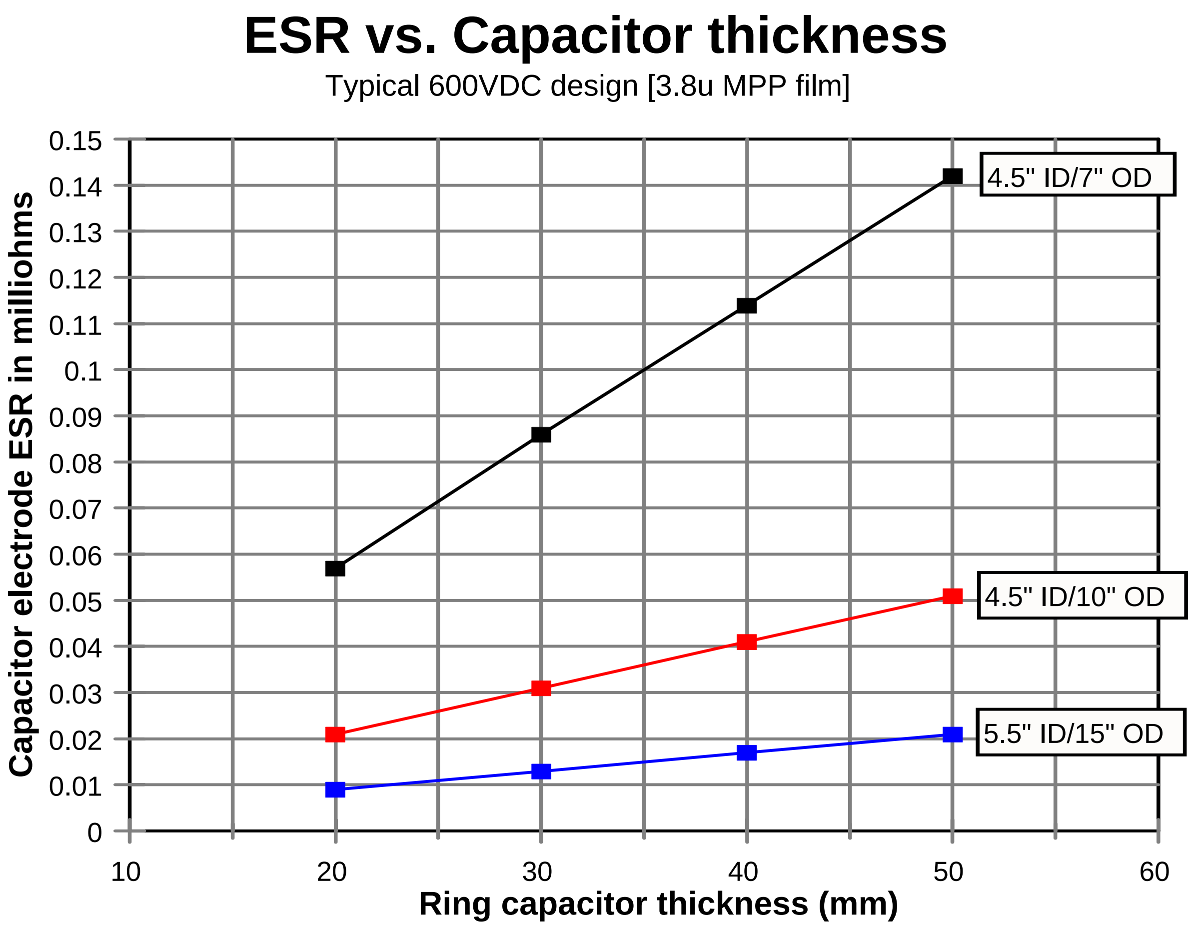

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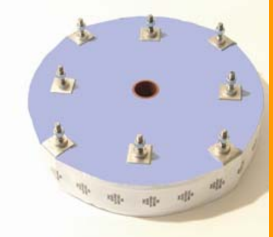
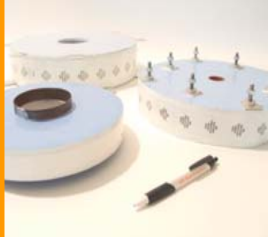
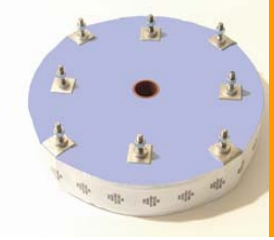


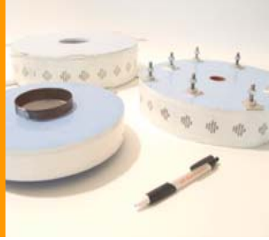
Trade-Offs for Increased Capacitance



- Reducing Film Thickness will also increase ESR and tend to reduce lifetime
- Increasing Ring Thickness will result in higher ESR and Thermal Resistance
- ESR and Thermal Resistance are prime drivers of Ripple Current Ratings



Ripple Current



- It's a function of Temperature
- MPP is usable from -55°C to +105°C, with possible upside (i.e., high crystallinity film)
- A "Current Rating" is near meaningless unless the thermal environment is well defined
- Traditional Capacitor Current Ratings usually assume "free air convection" (the fine print)
  - An invalid assumption for a Motor Environment

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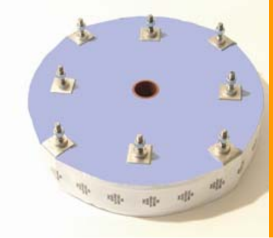
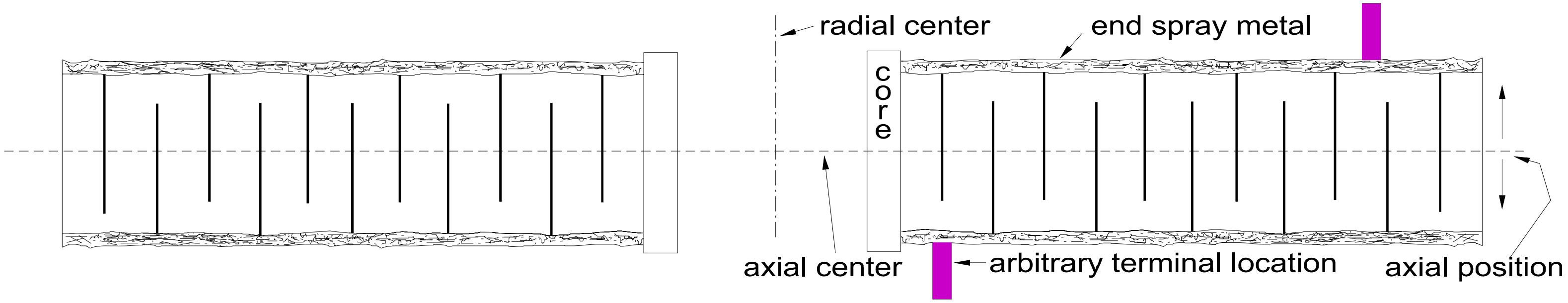


Ripple Current

- A Thermally Distributed Model Applies
  - The Capacitor will see different temperatures at different places
  - Thermal Conductivity is not uniform over the capacitor surface



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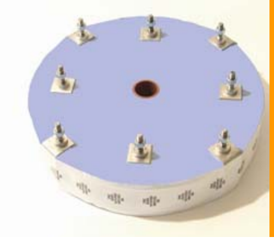
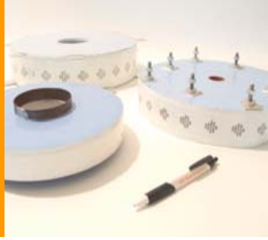


Ripple Current



- So, as a Capacitor Manufacturer, ***how*** do we Rate the Ripple Current?
  - We need to know the maximum temperature at the End Spray Surface

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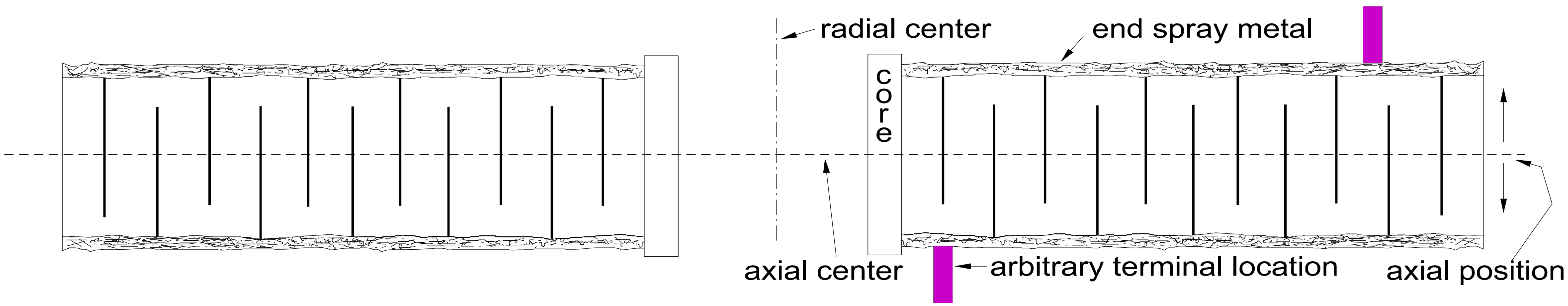

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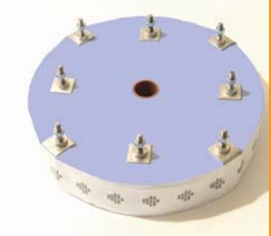
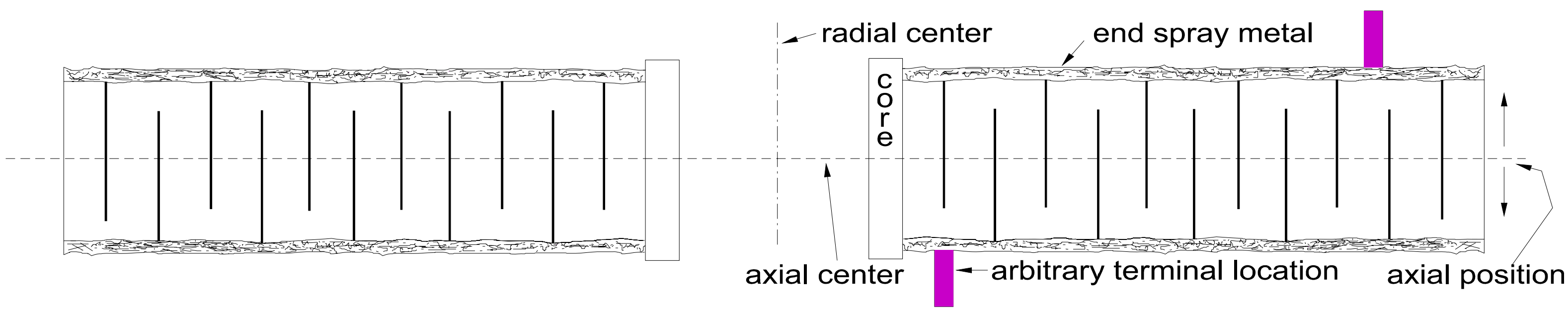


Ripple Current

- Unlike Conventional Capacitors, the Film Electrode Loss for the Ring Structure is so Low that current in the End Spray can be the dominant Loss Contributor
- Capacitor Interface with Bus Structure is Critical to minimize End Spray Losses and therefore will dictate the location of this maximum temperature
- Capacitor Hot Spot will be near the terminals



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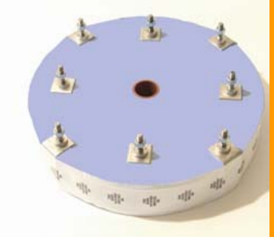
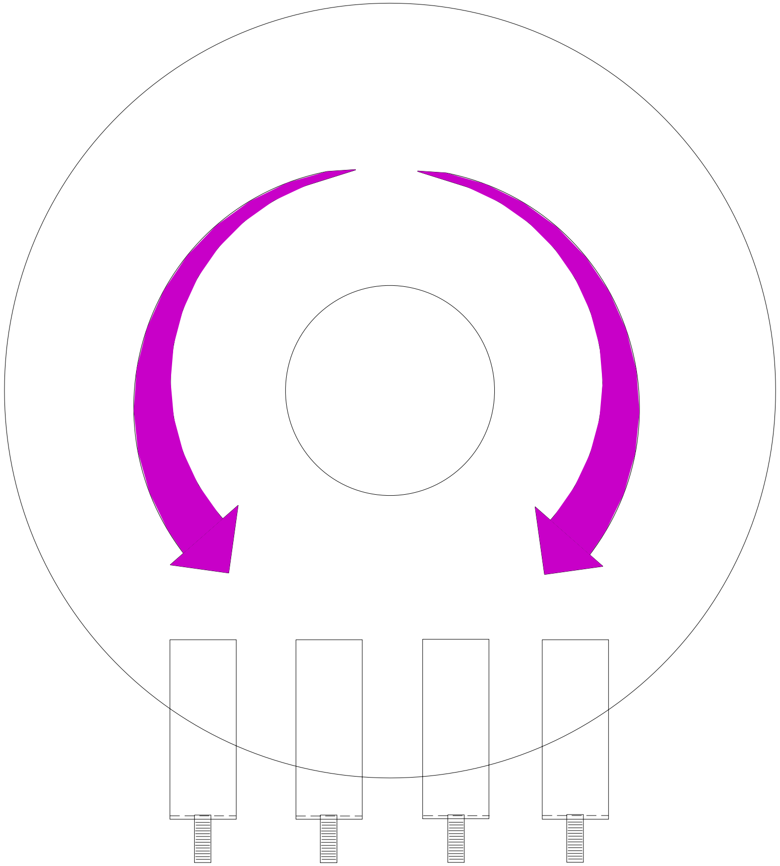


Ripple Current Rating affected by Terminal Placement



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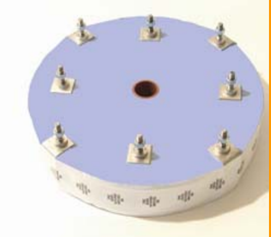

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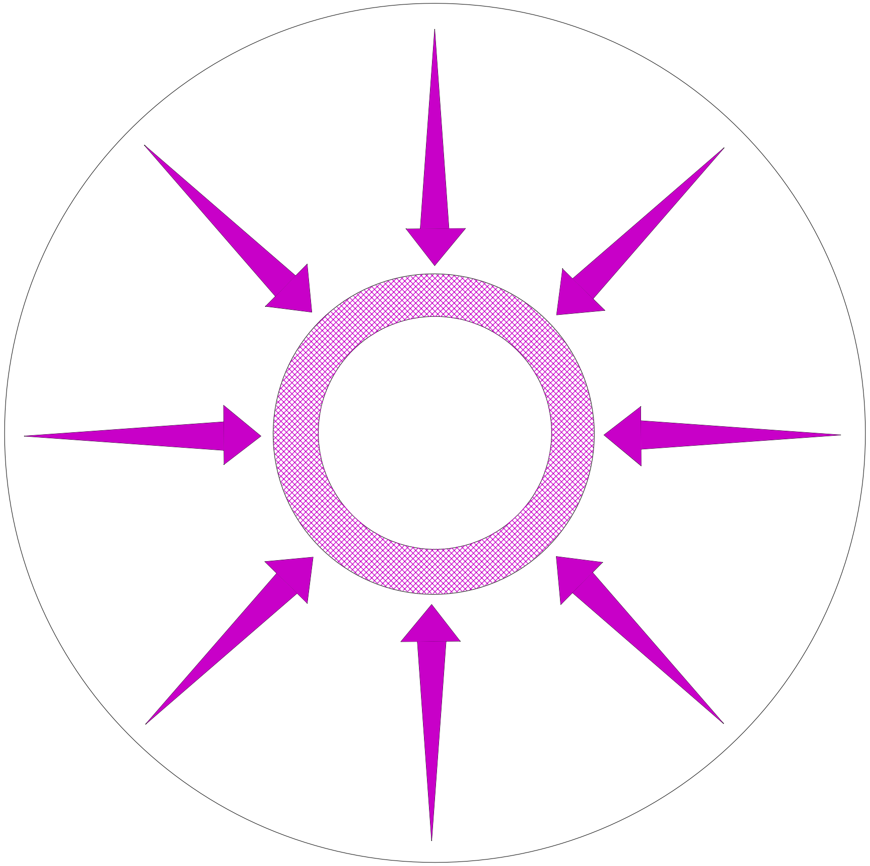

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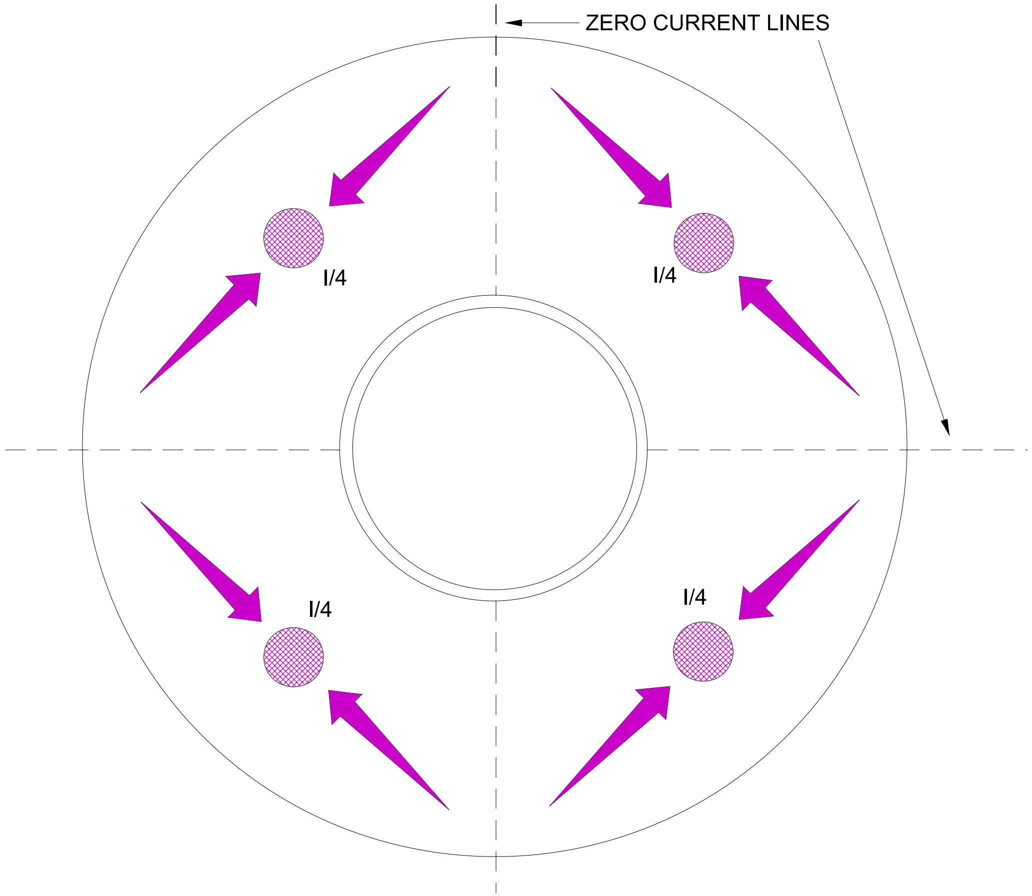

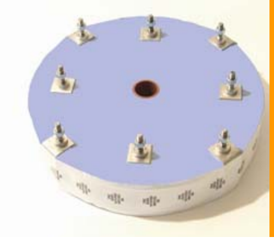

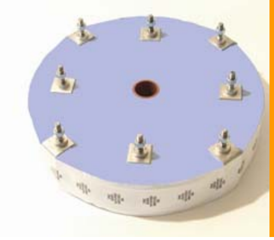

Ripple Current - Conclusions

- Reducing Current Density in the End Spray results in lower Heat Dissipation and a Higher Ripple Current Rating
  - Multiple Terminals and Optimal Placement Required
- Use of a Thin Ring results in a higher Ripple Current Rating
  - Lower Film Electrode Loss
  - Shorter Thermal Path
  - Doubling the Ring Thickness results in halving the Ripple Current Rating
- Reducing Capacitor Interconnect Losses will also increase the Ripple Current Rating

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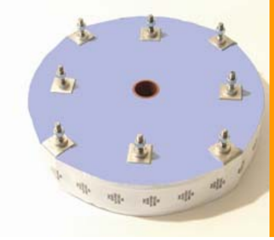

Capacitor Interconnect Losses

- Simulation and Experiments have shown that the Capacitor behaves as a Heat Sink for the Bus Structure Losses!
  - Only considers the AC case
- The DC Bus Losses make the above problem even more pronounced
- To Truly Optimize Ripple Current Rating, minimize Overall Bus Structure Losses

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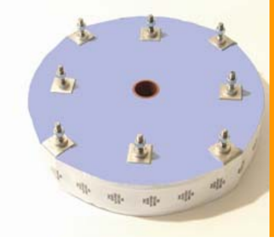
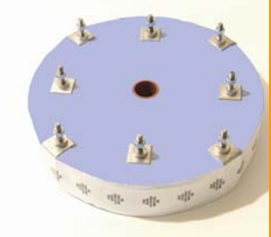
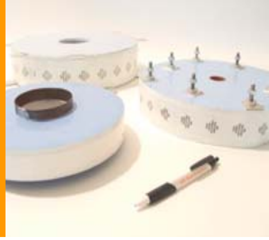


Bus Structure Losses

- Use the highest voltage that Semiconductor SOA and winding insulation systems will allow
  - Doubling the voltage will reduce bus dissipation by a factor of 4. Will not necessarily change Capacitor size.
- Skin Effect Losses can be significant
  - Multiple Connections reduce this effect
  - Be sure to consider the harmonic content of ripple current



The Value of Symmetry



- The most efficient performance is optimized by Electrical and Mechanical Symmetry
- For 3 Phase Systems, the Inverter power should be withdrawn from the bus at equally spaced locations (120 degrees apart)
- If the DC Input is very close to one of the Inverter outputs, the DC losses can be minimized

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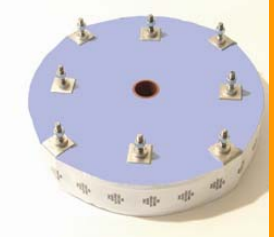

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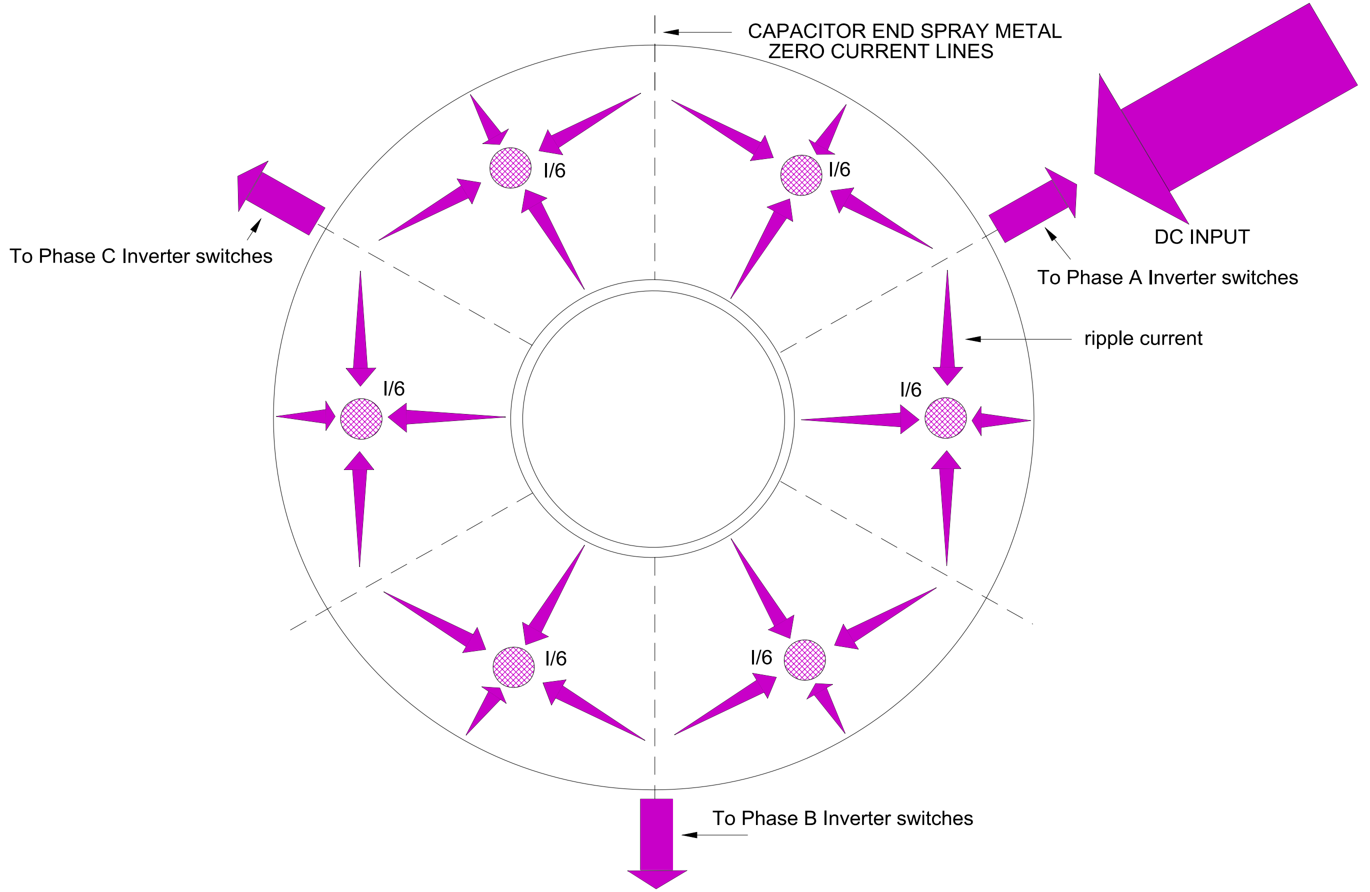

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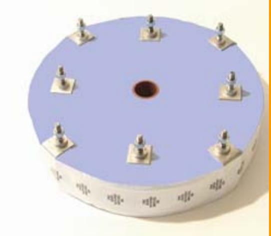

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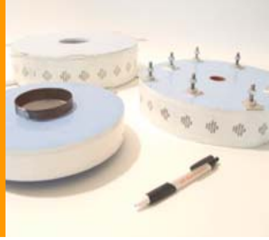

- 6 areas on the Capacitor surface with essentially no dissipation (zero current)
- 6 terminals divide the ripple current, further reducing dissipation
- Remove DC power to inverters between interconnects to more uniformly distribute the ripple current
- Apply DC input current very close to the inverter AC outputs to minimize DC losses in the Bus Structure

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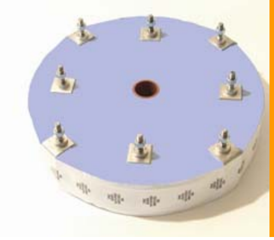
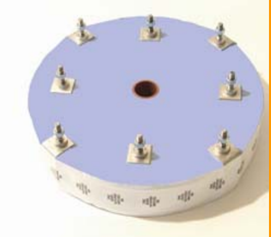


Conclusions

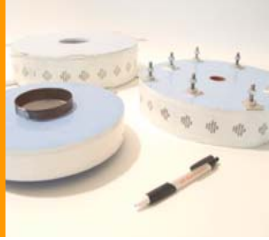
- There are great advantages when committed to a round shape of the Capacitor/Inverter

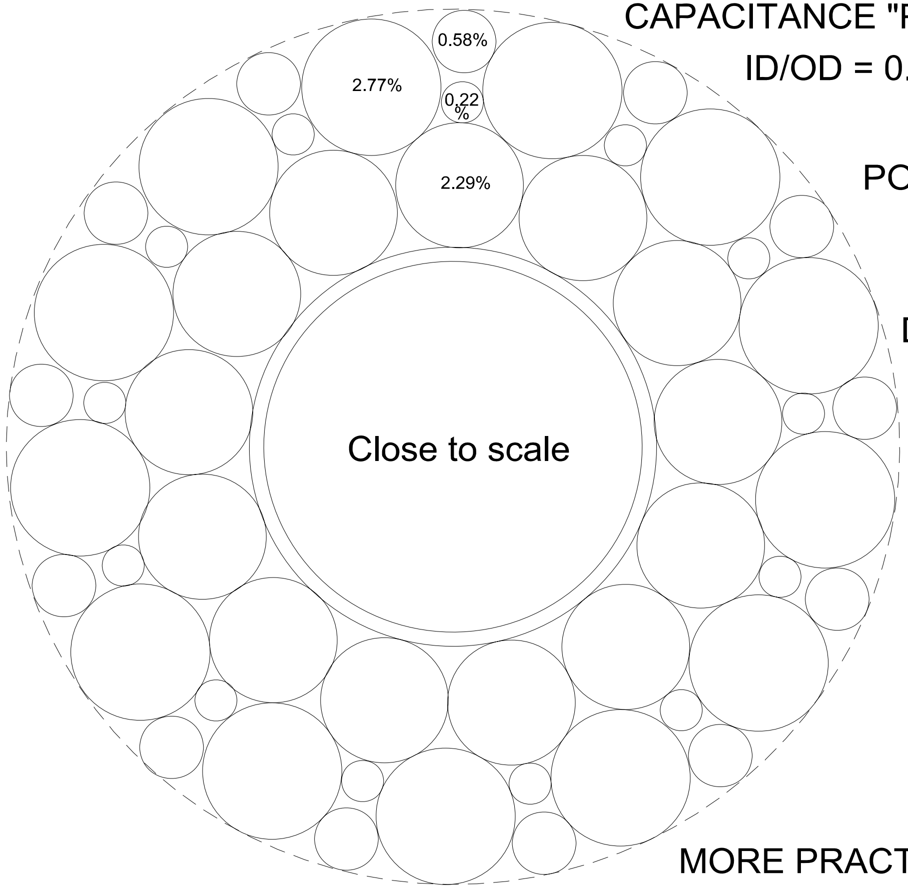
- To obtain optimum performance from your E-Drive System, close interaction with the Capacitor Manufacturer is required

- The advantages of the Power Ring over a discrete implementation are significant in both space and allowable ripple current
  - Ripple current has to be reduced by the “Packing Factor” percentage



What is the Difference between the Discrete Implementation and the Solid Ring Approach?





CAPACITANCE "PACKING FACTOR"

ID/OD = 0.47 for this example.

POWER RING: 100%

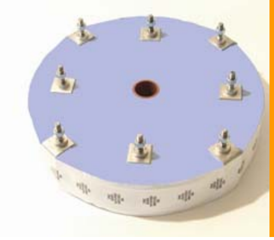
EXTREME PARALLEL
DISCRETE SOLUTION:

2.77% * 13 = 36%
2.29% * 13 = 30%
0.58% * 13 = 8%
0.22% * 13 = 3%
TOTAL 77%

MORE PRACTICAL SOLUTION: 66%

SB ELECTRONICS

SBE



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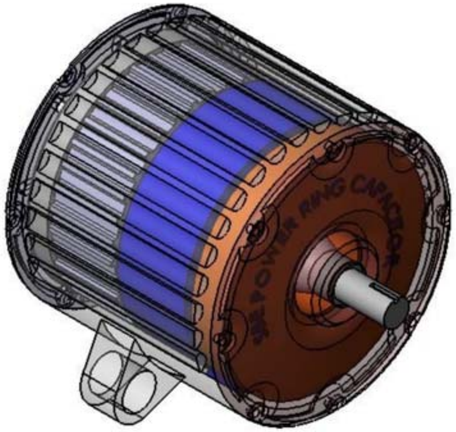

Thank you!

Come see us at Booth 23

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