Stray Losses in Power Transformers

Transformer Concepts & Applications Seminar

Goldsboro, NC

Sep 17–19, 2024

waukesha
a prolec ge company

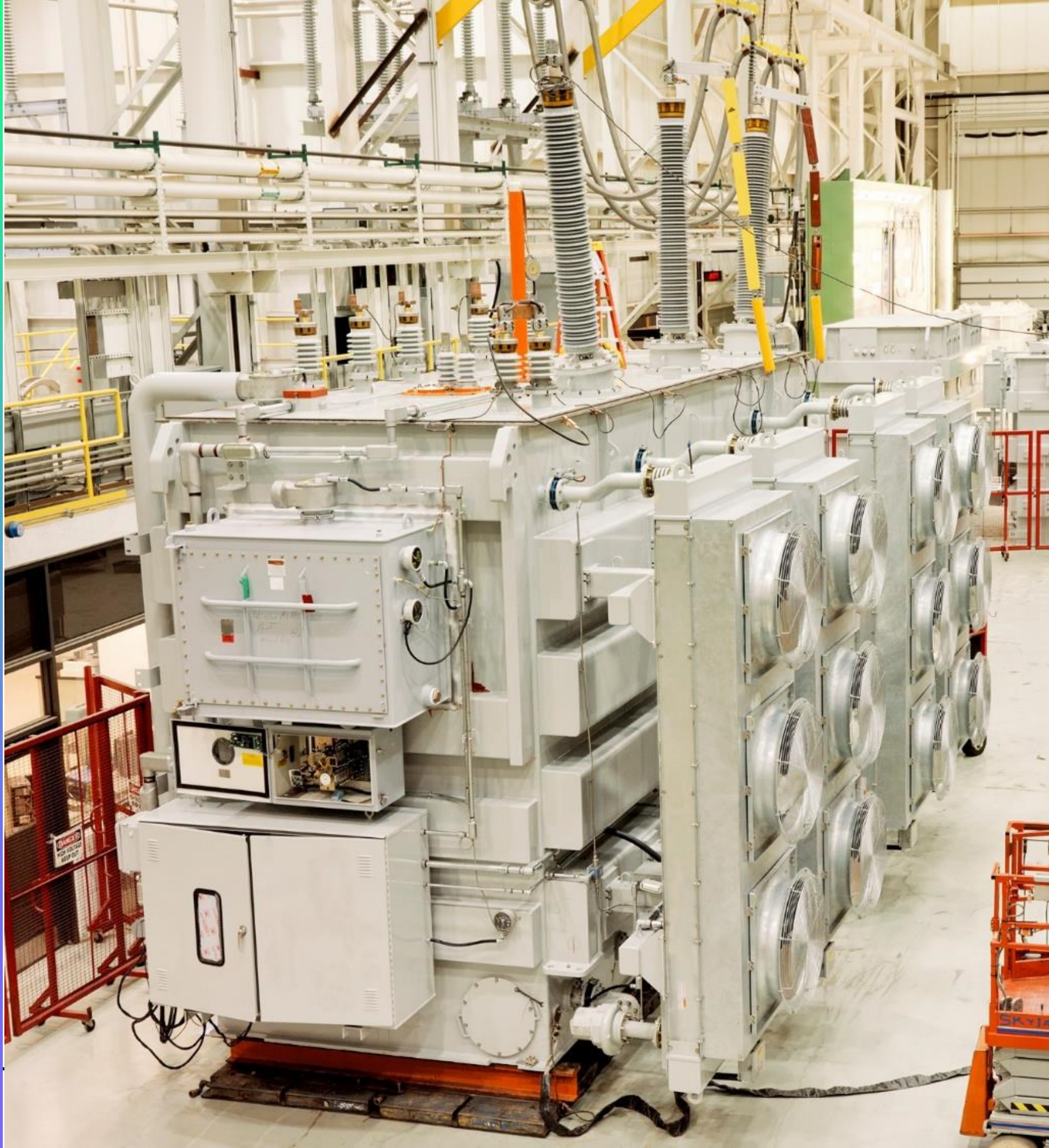
Pradeep Ramaswamy
Design & Development Engineer

Pradeep joined Prolec GE Waukesha in October 2008 and has 20 years of expertise in Electrostatic & Electromagnetic FEA analysis of transformers. He specializes in GIC and electromagnetic threat assessment of transformers, design review & troubleshooting calculations, system interaction studies and new product development for smart grid applications. Pradeep has a bachelor's degree in Electrical & Electronics Engineering and a master's degree in Electrical Engineering. He has a number of publications in CIGRE Paris sessions and other international conferences. He was also recognized as an exceptional reviewer for IEEE transactions on Power Delivery.

www.linkedin.com/in/pradeep-ramaswamy

https://prswamy.wordpress.com/

waukesha
a prolec ge company



Agenda

- Definition
- Formation & Characteristics
- Detrimental Effects & Design Countermeasures

Transformer Power Loss

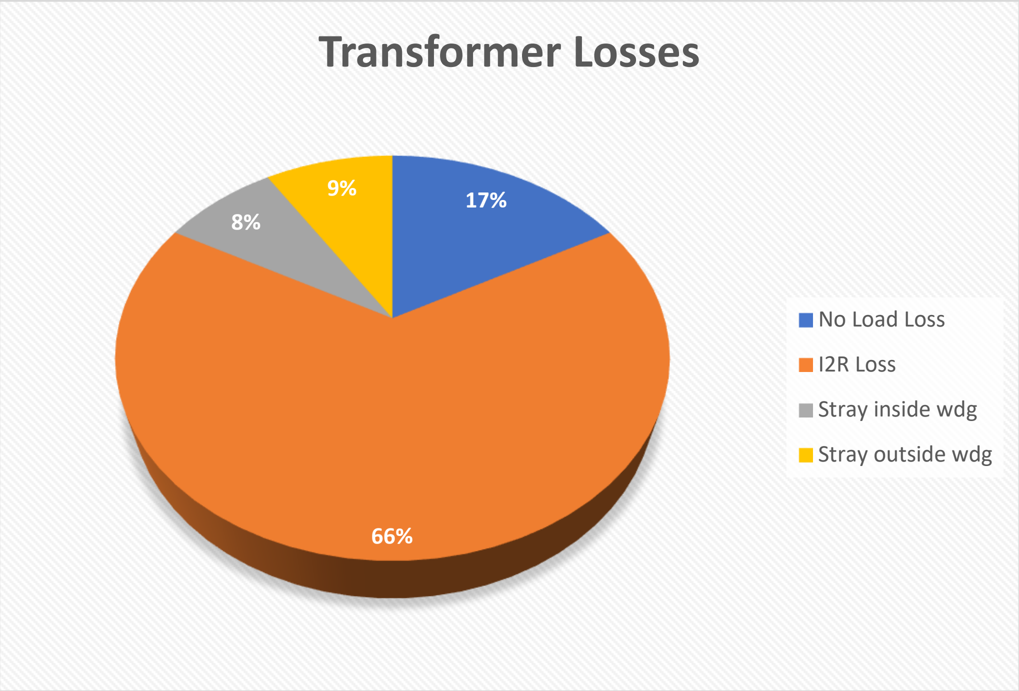
- **Transformer losses typically lumped into:**
  - **No-Load loss or Core Loss.**
    - **Core Eddy Loss**
    - **Core Hysteresis Loss**
    - **Core Excess Loss**
- **Load Loss**
  - **I^2R Loss or DC loss**
  - **Stray Loss inside winding or Wdg Eddy loss**
  - **Stray Loss outside winding**

Transformer Power Loss – Typical Magnitudes

waukesha
a prolec ge company

- **Total loss < 0.5% of total transformer rating.**

Rating	360 MVA	100%		
Total Loss	504 kW	0.1400%	100%	
• No Load Loss	84 kW	0.0233%	17%	
• Load Loss	420 kW	0.1167%	83%	100%
• I^2R Loss	332kW	0.0922%	66%	79%
• Stray inside wdg	43 kW	0.0119%	8%	10%
• Stray outside wdg	45 kW	0.0125%	9%	11%



Overview

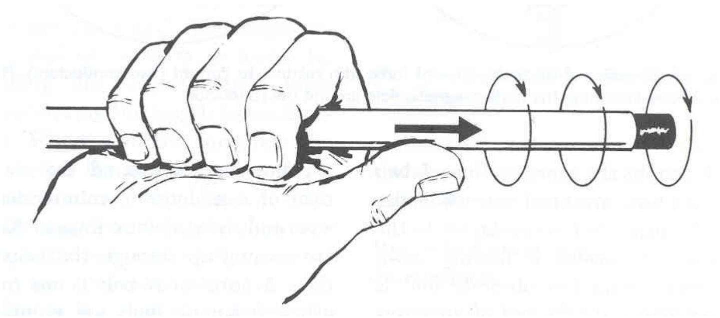
- Stray loss is a component of Load Loss.
- Stray magnetic fields are formed when load current flows in coils or leads.
- Stray magnetic fields form closed loops around the conductors and through the tank walls, core clamps, tieplates, etc, inducing stray losses in these components.
- Heating and gassing caused by stray losses must be understood to allow reliable operation of the transformer throughout its life.
- There are various ways to minimize / control stray losses.

Two Components of Transformer Stray Loss

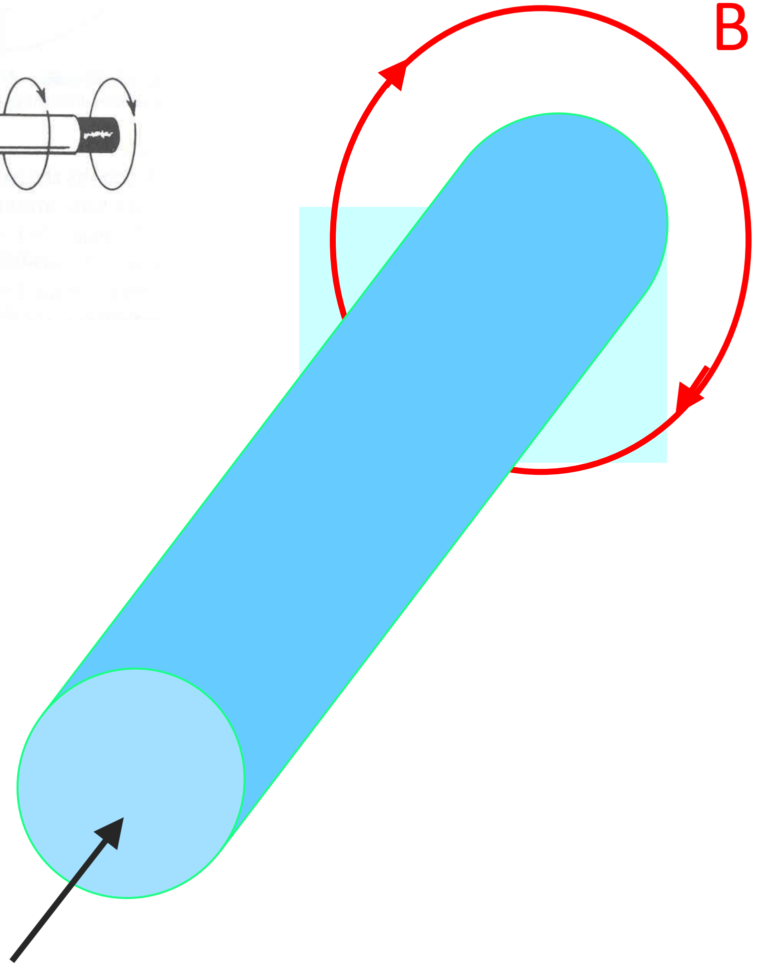
1. Coil stray flux field:
   - Formed in the duct between coils.
   - Excited when load current flows.
   - Proportional to the load current.
   - Losses are generated in coil conductors & metallic structures

2. Ancillary lead stray flux fields:
   - Formed in the cylindrical volume surrounding bushings, coil interconnecting leads, etc.
   - Excited when load current flows
   - Proportional to the load current.
   - Losses generated in metallic structures.

Current/Flux Relationship



Right hand rule

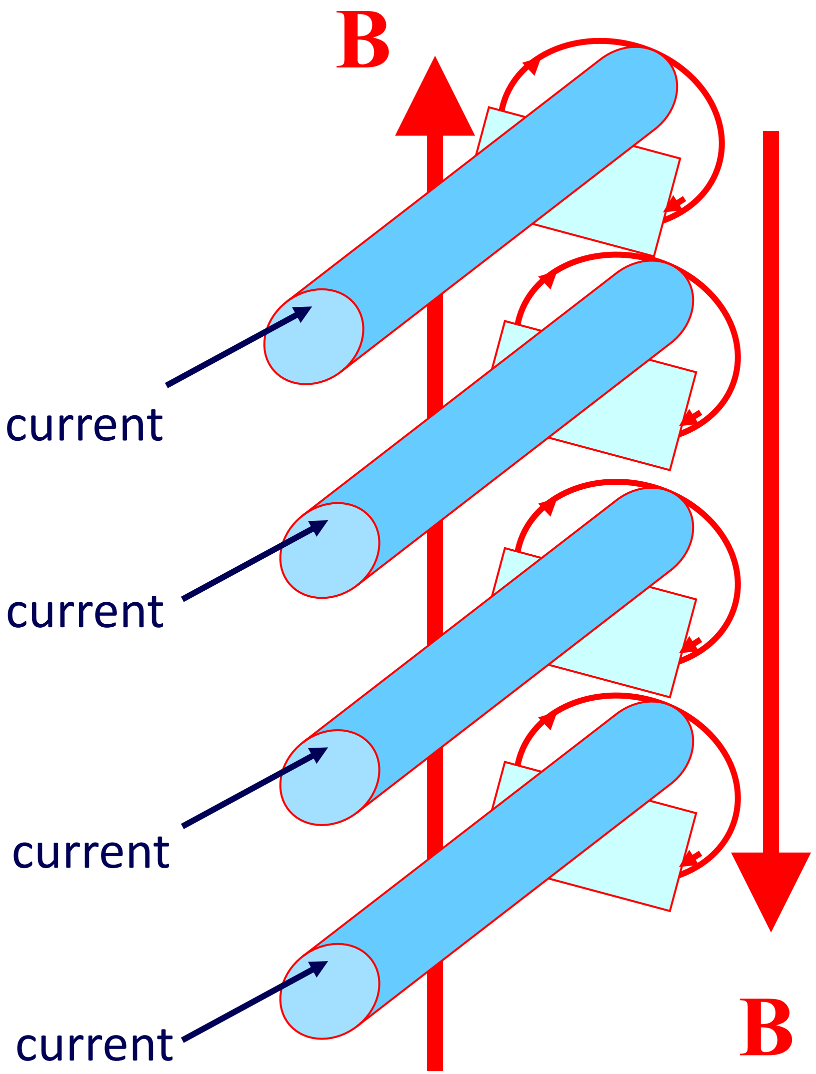


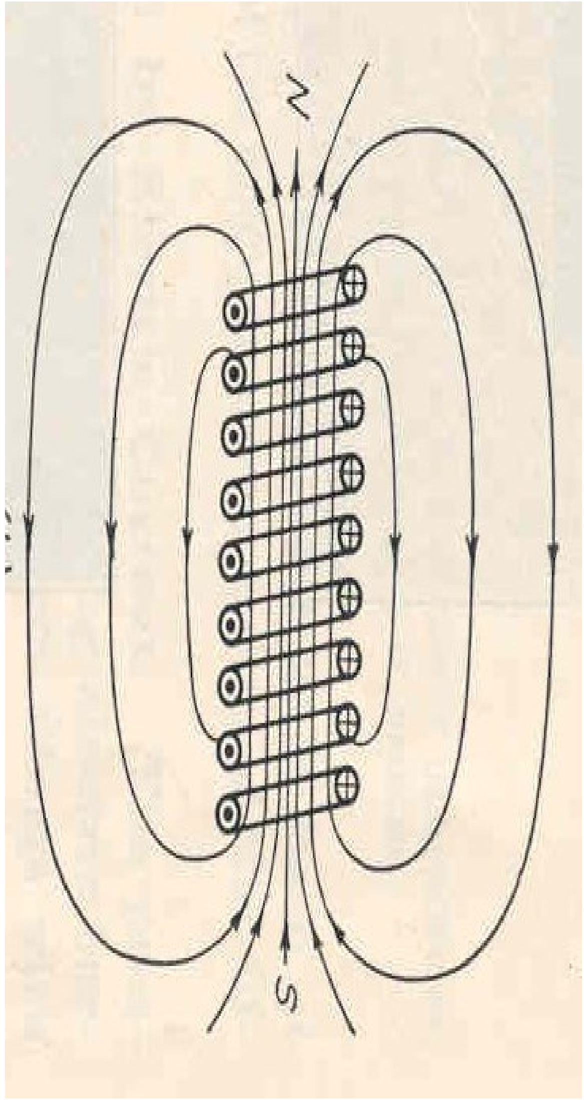
Resulting Magnetic Field Direction (CW)

Current Flow (I)

$B \propto I$

Current/Flux Relationship

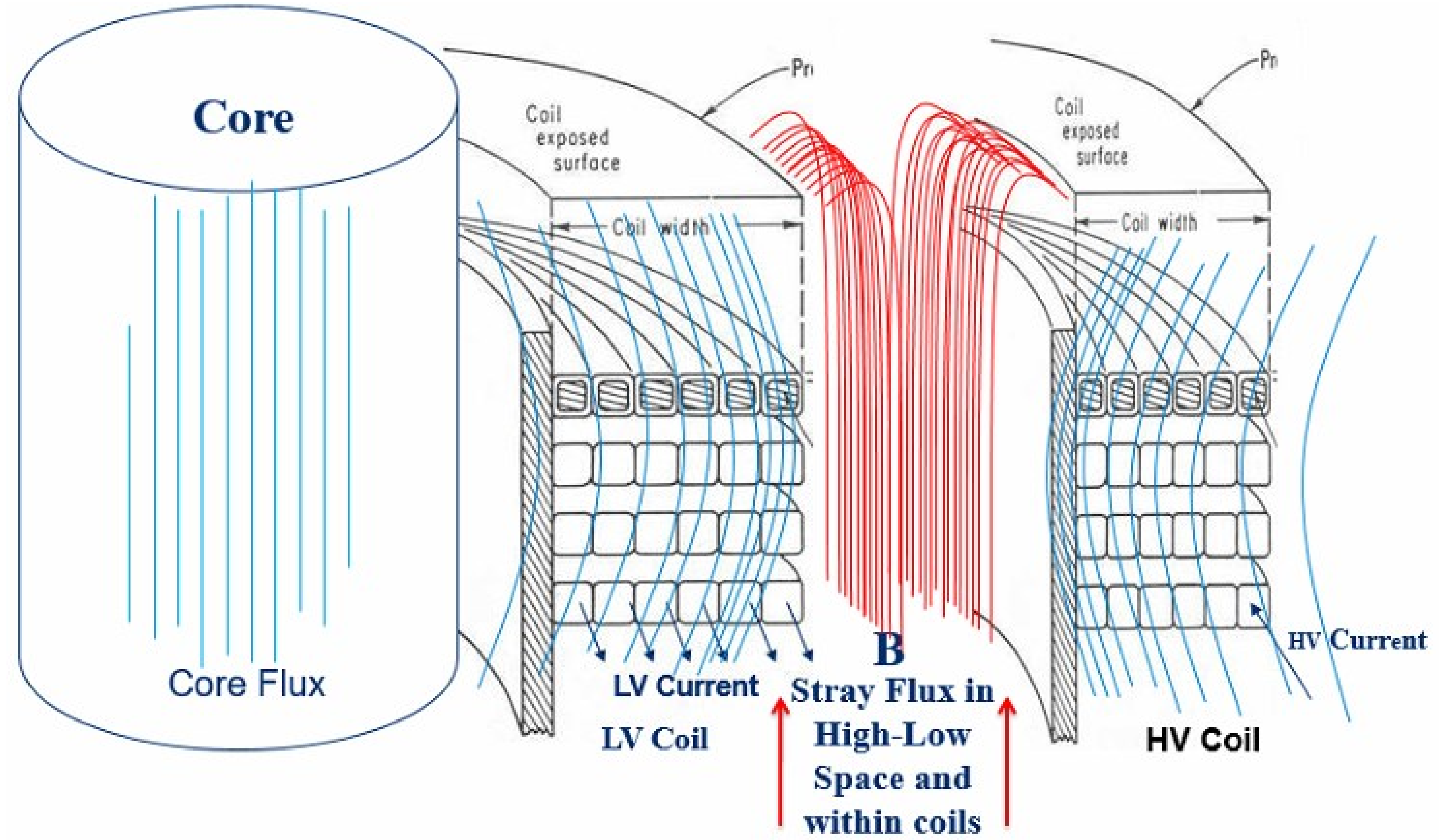




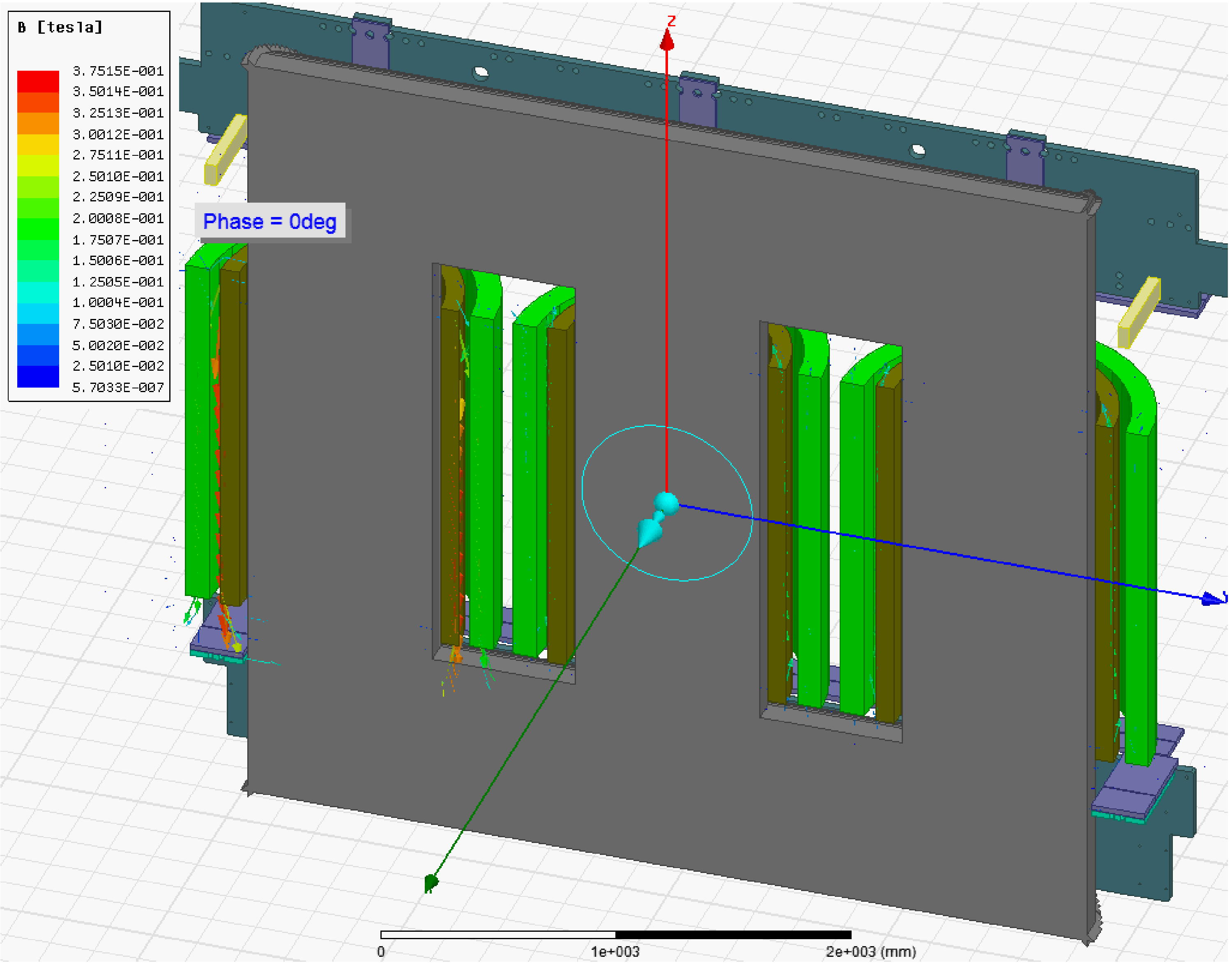
- Fields at inner/outer edges add together.
- One uniform magnetic path results
- Magnetic field (B) intensifies with # turns (N) or the current (I).

$$B \propto NI$$

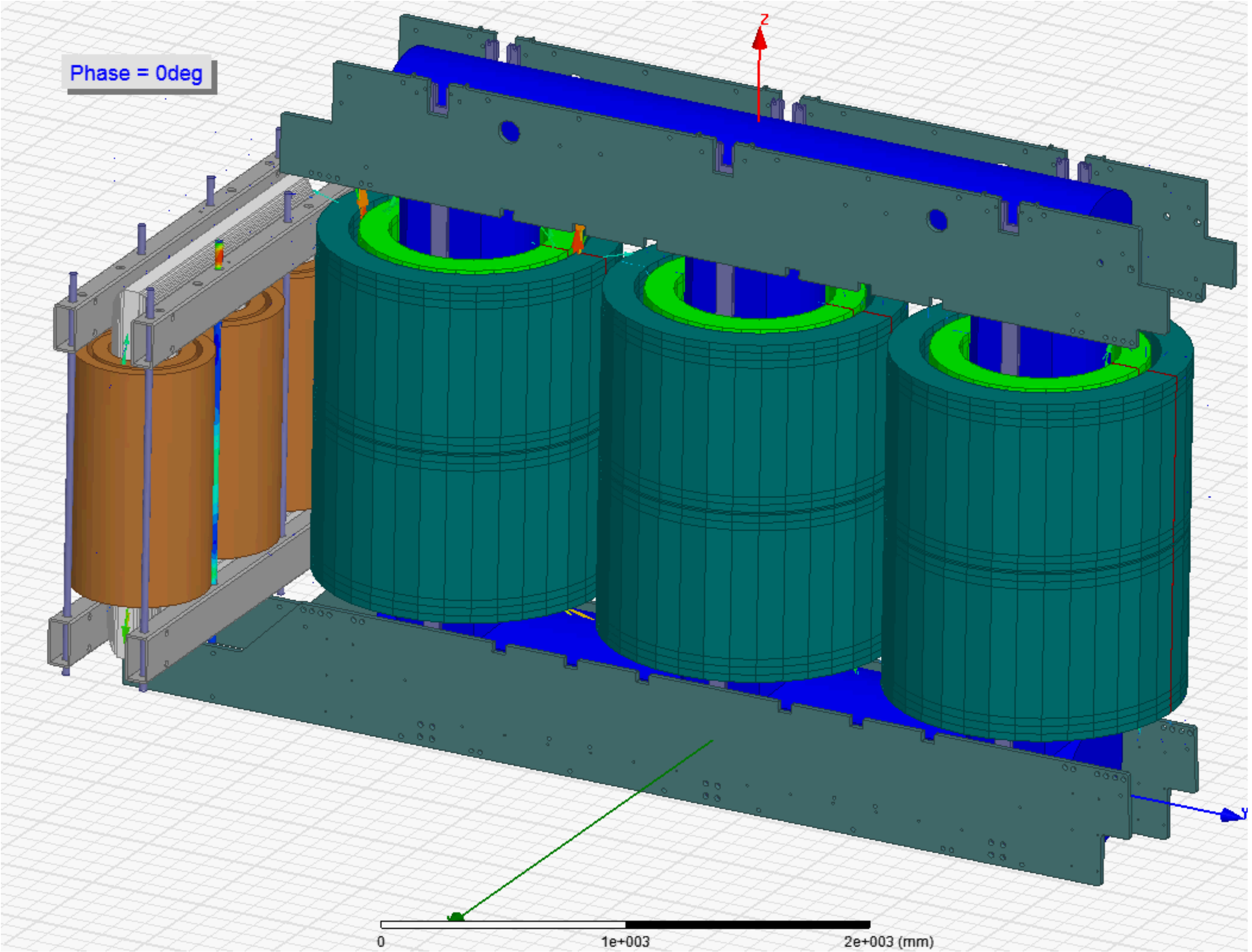
Concentric Coils Showing Stray Flux



Concentric Coils Showing Stray Flux

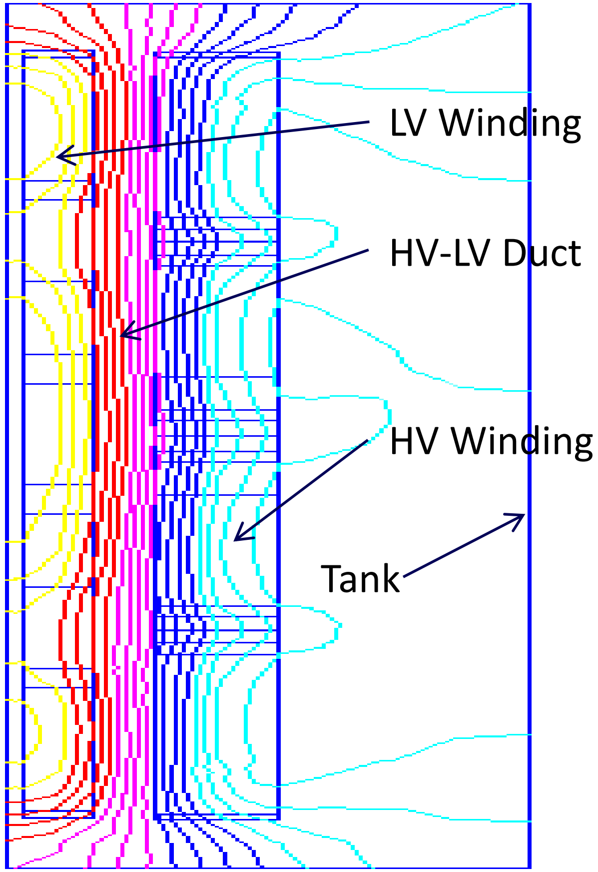


Concentric Coils Showing Stray Flux with Booster

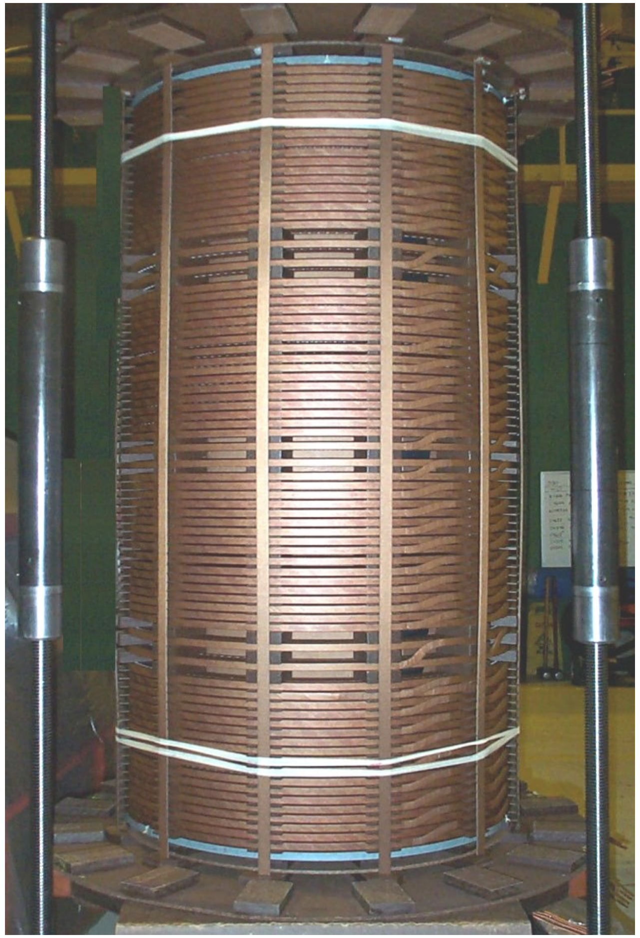


Stray Flux Plot

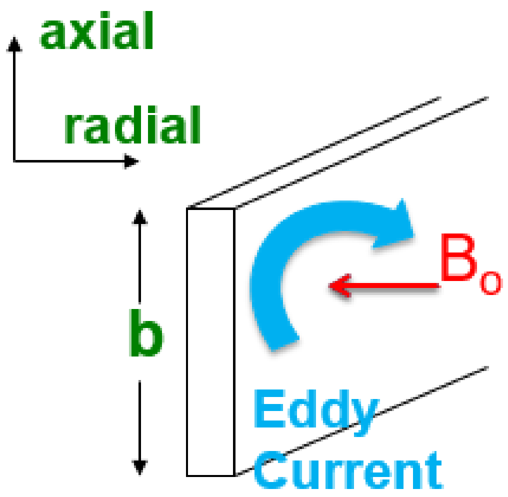
Stray Flux "leaks" out radially whenever there is an axial spreading out of turns in a coil



Finite Element Analysis of Leakage Flux Between Coils



Stray Loss or Eddy Current Loss in Conductors



Eddy Current Loss (W/m^3) = $(\pi^2/6)(f\ bB_o)^2/\rho$

f = 60 Hz

B_o = Peak Induction acting ⊥ to side length b

- The stray flux is resolved into ⊥ components in the axial and radial direction of the conductor. The same formula then applies to the radial conductor surface.
- Reducing conductor thickness or width by 1/2 reduces the losses by 1/4.
- The conductor stray losses vary with the position of the conductor, since the stray flux varies with location. The magnitude of the radial flux is higher at the ends of the winding, resulting in higher eddy current losses and higher conductor temperatures.
- Conductor hot spot is at the top of the coil - - Highest local stray loss and hottest oil.

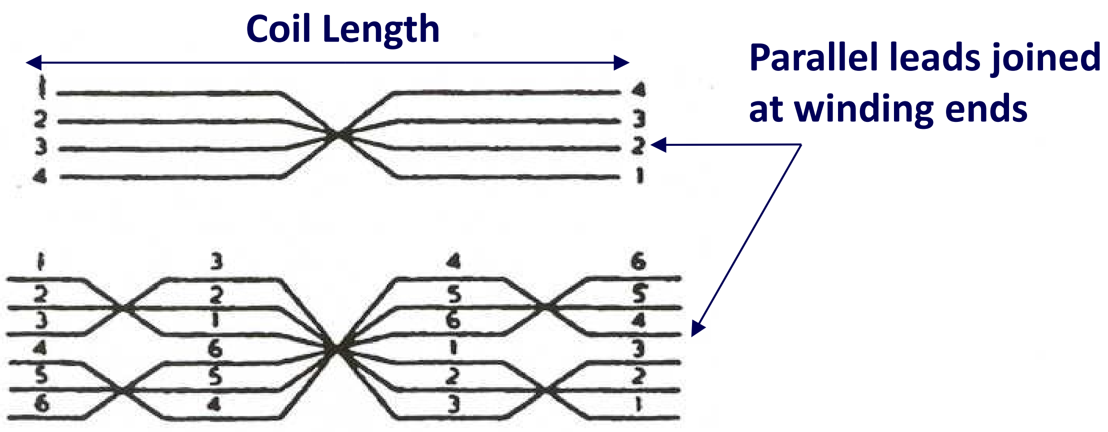
Stray Loss Reduction – Within the Winding

Conductor Max Hotspot Temp limits per IEEE C57.91 Overload Guide:

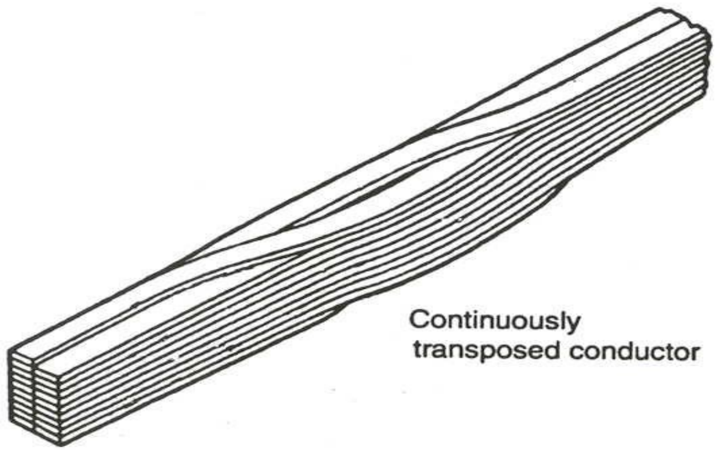
- Nameplate operation – 120°C Max
- Long term Emergency Overload Operation – 140°C Max

Coil Design Options:

- Mag Wire - Reduce conductor dimensions & increase # parallel strands
  - Transpose conductors – Each conductor occupies every radial position for an equal length
- Use CTC



Forms of transposition


Continuously transposed conductor

Stray Loss – Outside Winding

Stray flux is attracted to and will concentrate in the magnetic structural members:

- Tieplates & Core outer packet
- Side & End Clamps / bars
- Tank walls due to both coil and nearby high current leads / busbar stray field
- Turrets and Tank Cover due to High current bushing conductors / busbar

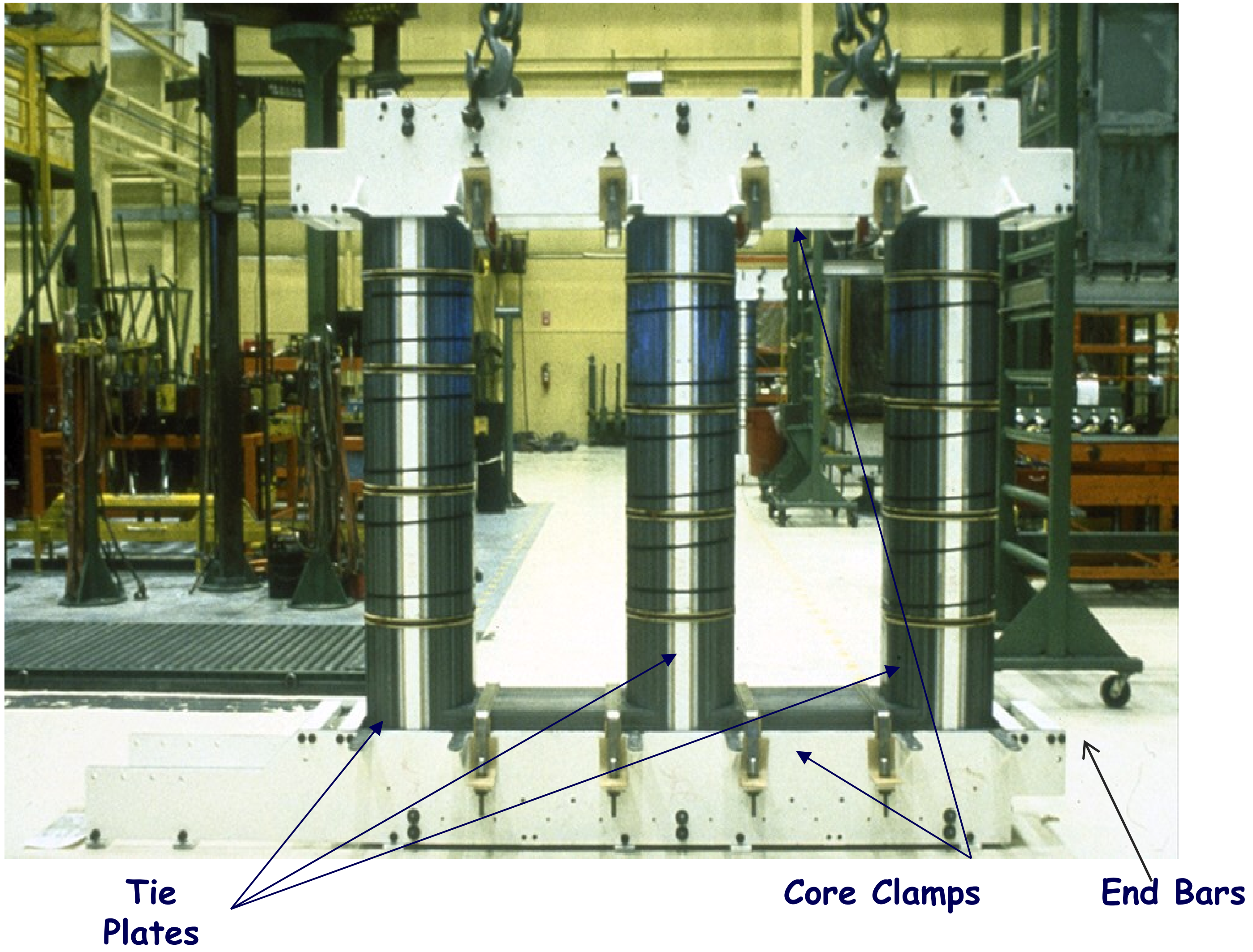
If the flux density becomes too great, excessive temperature rise is always the resulting problem.

“Other Metallic” Max Hotspot Temp limits per IEEE C57.91 Overload Guide:

- **Nameplate Operation – 140°C**
- **Long Term Emergency Overload Operation – 160°C**

Stray Loss – Outside Winding – Critical Components

- Tieplates: used to compress and hold both core and coil and also for lifting the same
- Clamps: used to compress and hold core
- Loss calculation from radial flux hitting tie plates and clamps is similar to loss calculation in conductor strands due to $\perp$ flux.

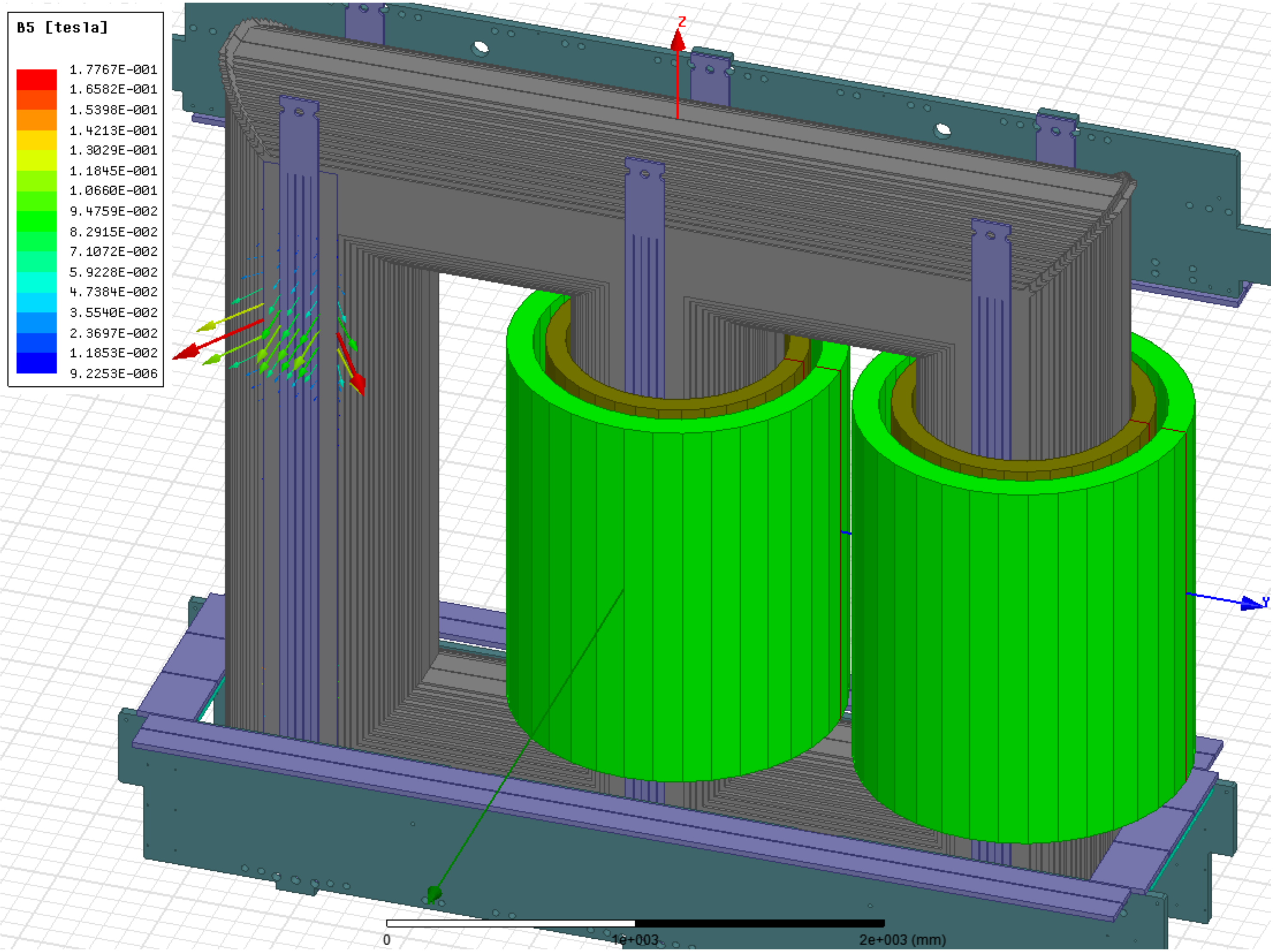


Stray Loss Control – Outside Winding

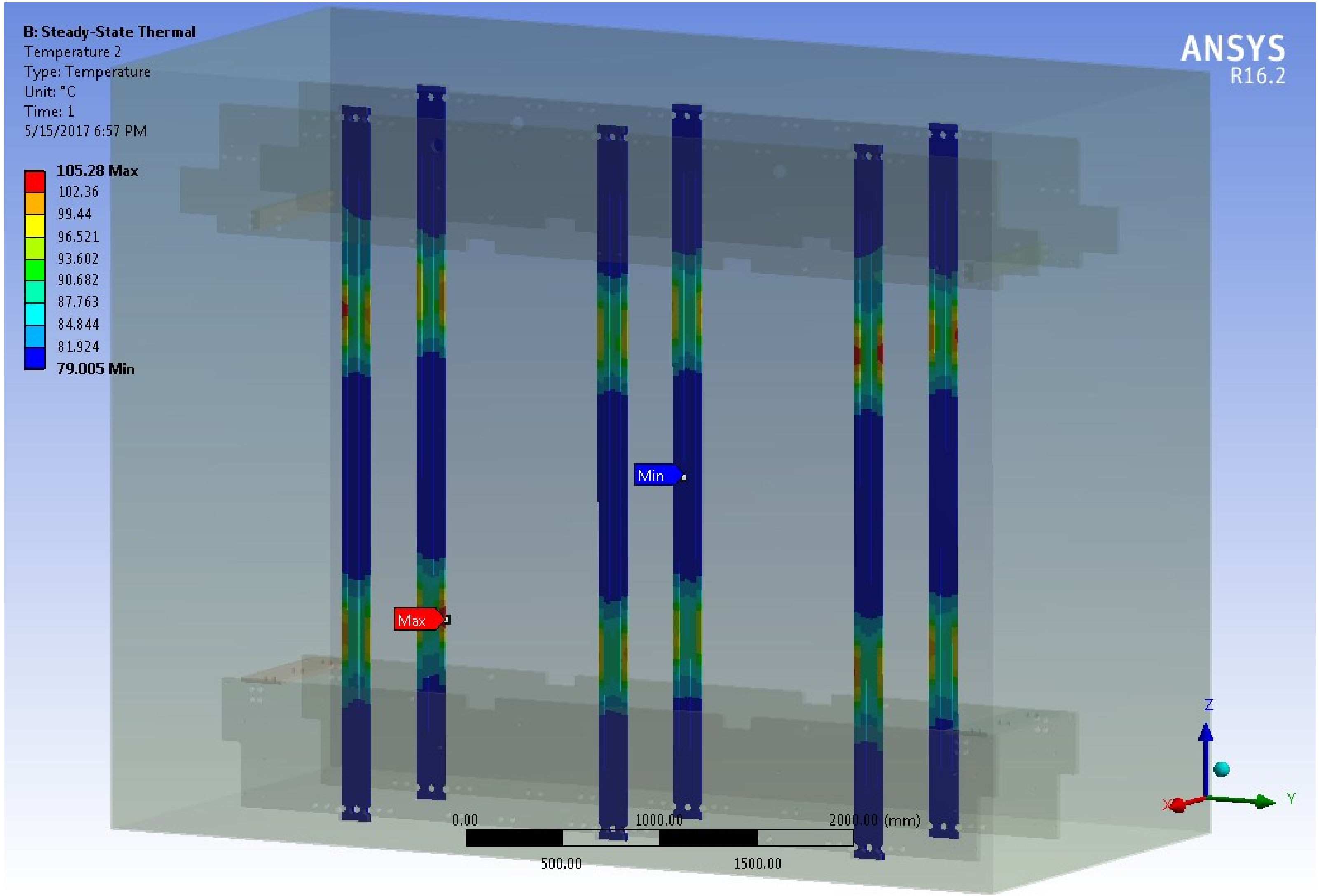
To Reduce Stray Loss and Its Heating Effect:

- Reposition or Segment Magnetic item - reduces eddy currents and thereby temperature.
- Replace magnetic steel item with non-magnetic stainless steel – item no longer attracts stray flux.
- Magnetic shunt – attracts and re-directs the stray flux through its low loss path.
- Non-magnetic shield (Cu / Al) - absorbs a small amount of flux, which generates low loss internal eddy currents, which in turn repel the remaining stray flux.
- Position phases of high current leads in close proximity to one another – (magnetic fields cancel).

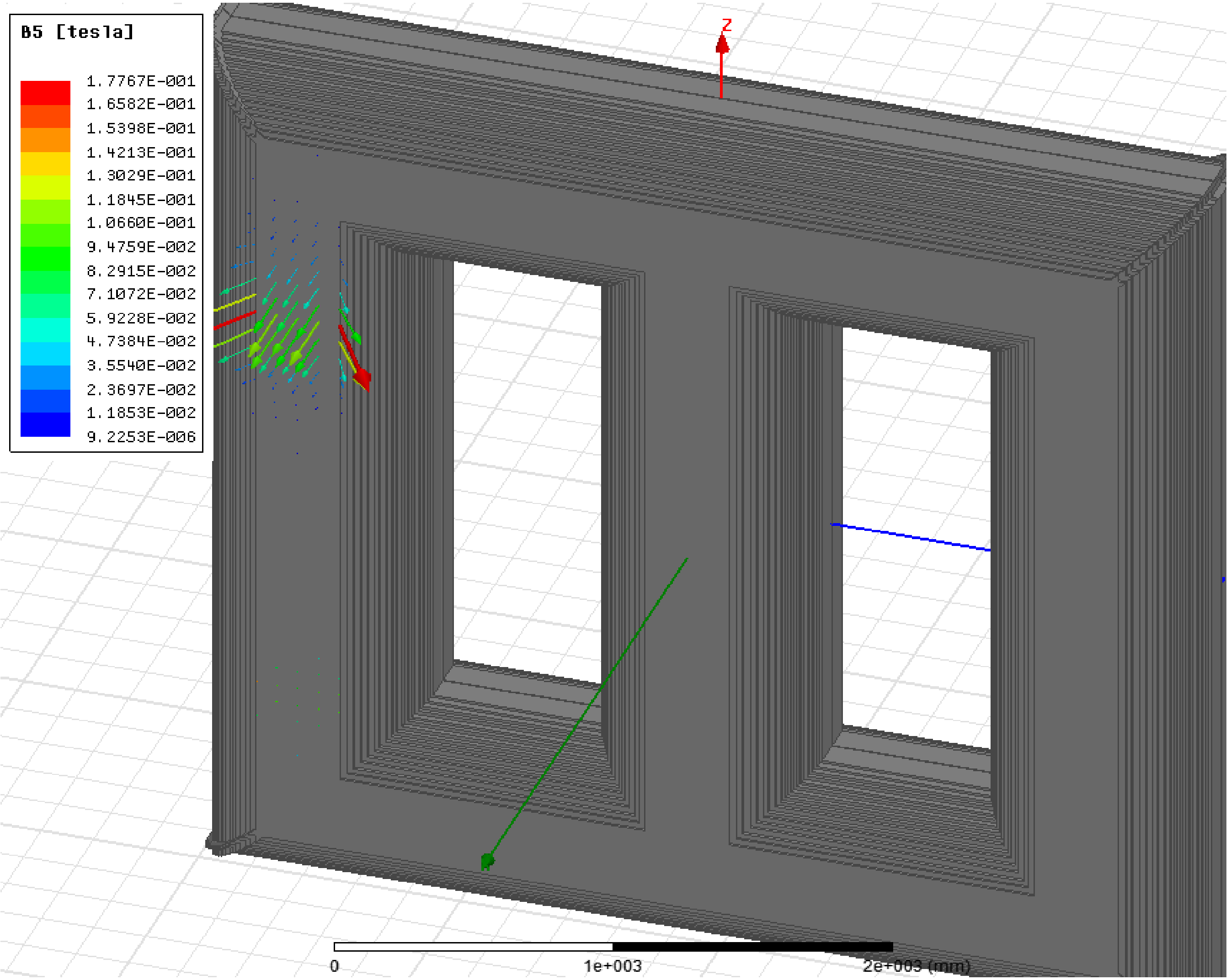
Stray Flux Incident on Tie Plates Radially



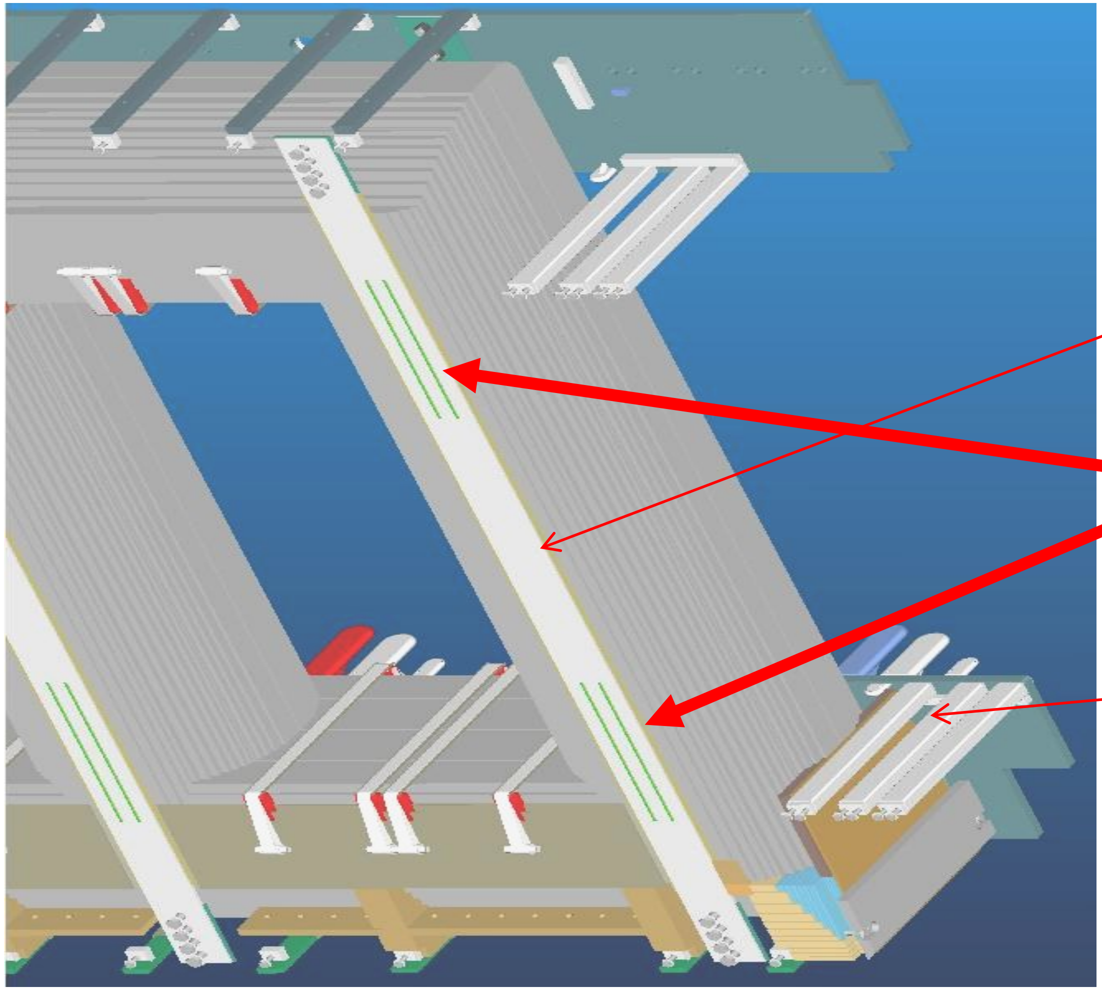
Stray Flux Heating of Tie Plates



Stray Flux Heating of Core Outer Packet



Segmented Magnetic Tieplate / End Bar / Outer Core Stray Loss Reduction Outside Windings

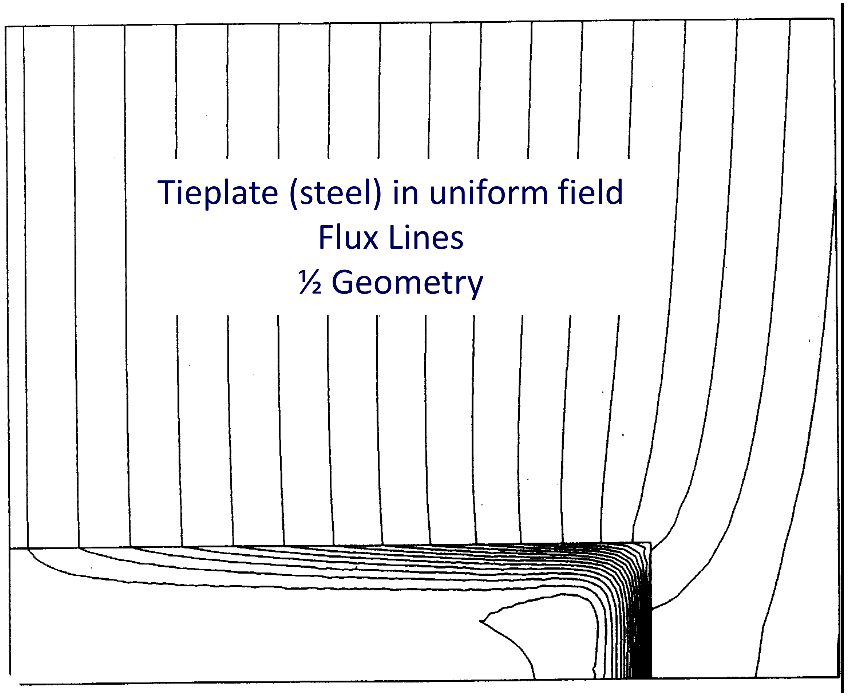


Divided Outer Core Packet

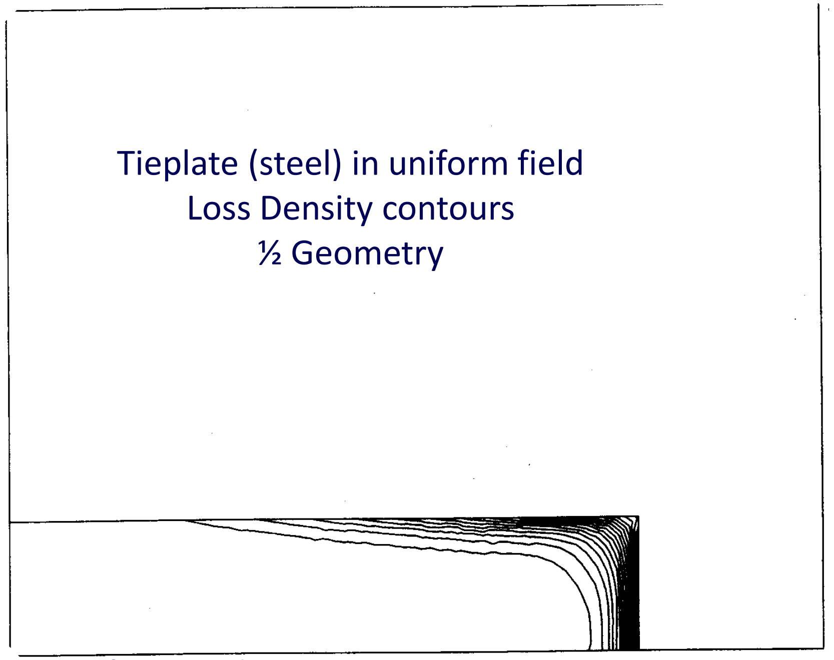
Slotted Tie Plate

Segmented End Bars

Magnetic Steel Tieplates – Stray Loss Outside the Windings



flux plot



loss density contours

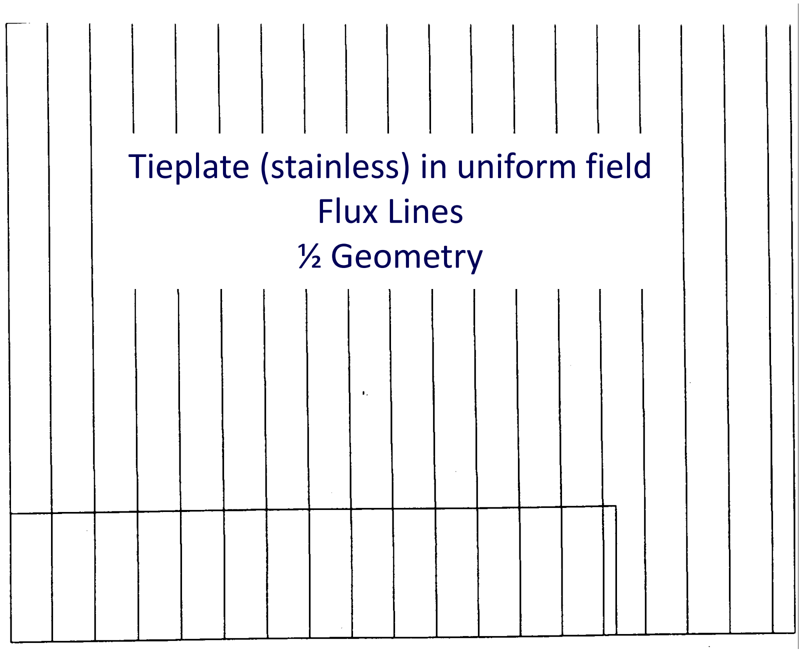
Magnetic steel loss (kW/in) = $0.10\ w^{2.4}\ B^2_{rms}$

w = tieplate width in inches

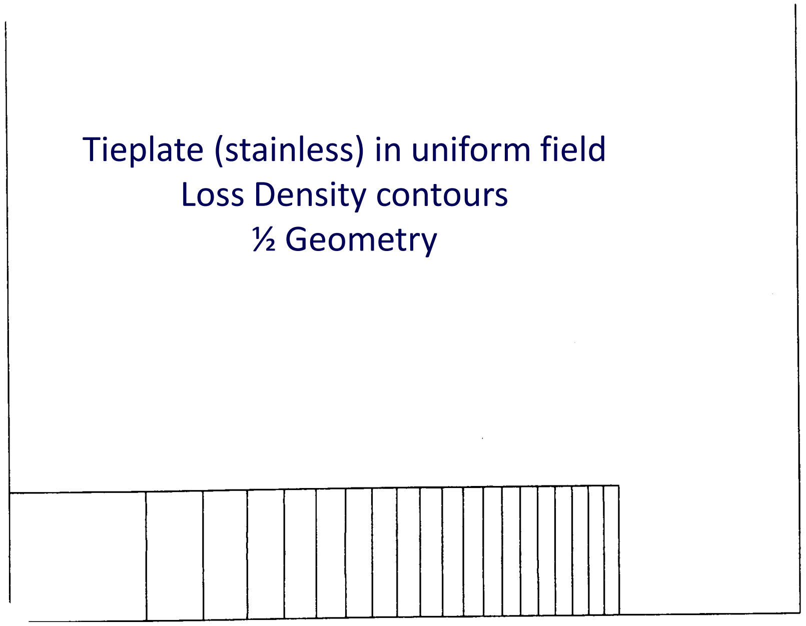
B_{rms} = rms radial induction in Tesla

To reduce these losses, tieplates are divided into smaller segments

Magnetic Steel Tieplates –
Stray Loss Reduction Outside the Windings



flux plot



loss density contours

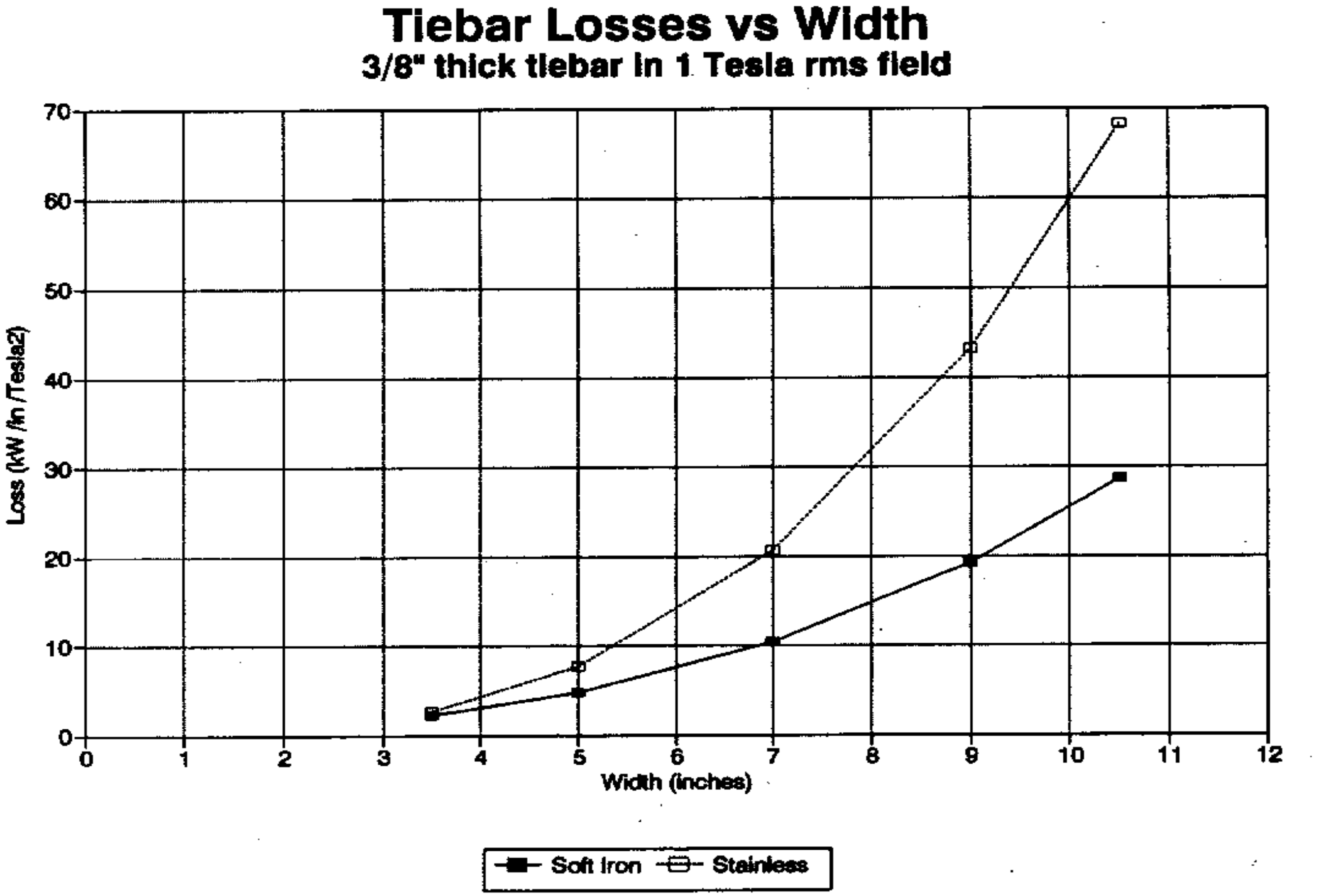
Stainless steel loss (kW/in) = $0.06\ w^3\ B^2_{rms}$

w = tieplate width in inches

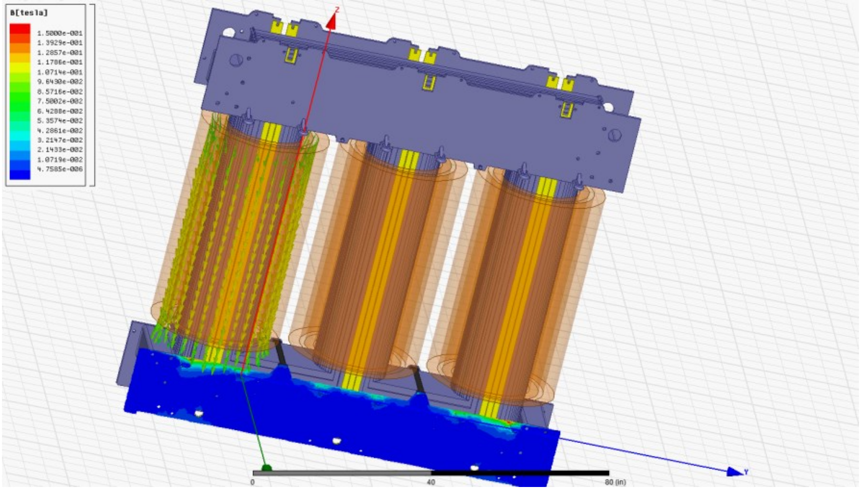
B_{rms} = rms radial induction in Tesla

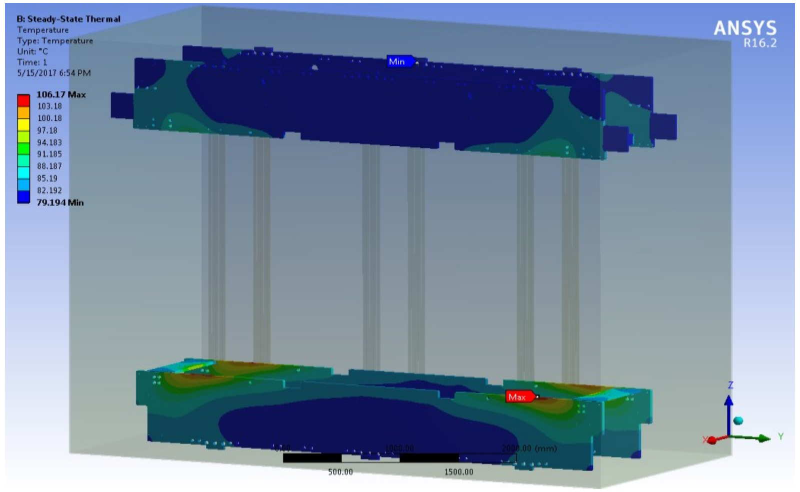
Used for large GSU.

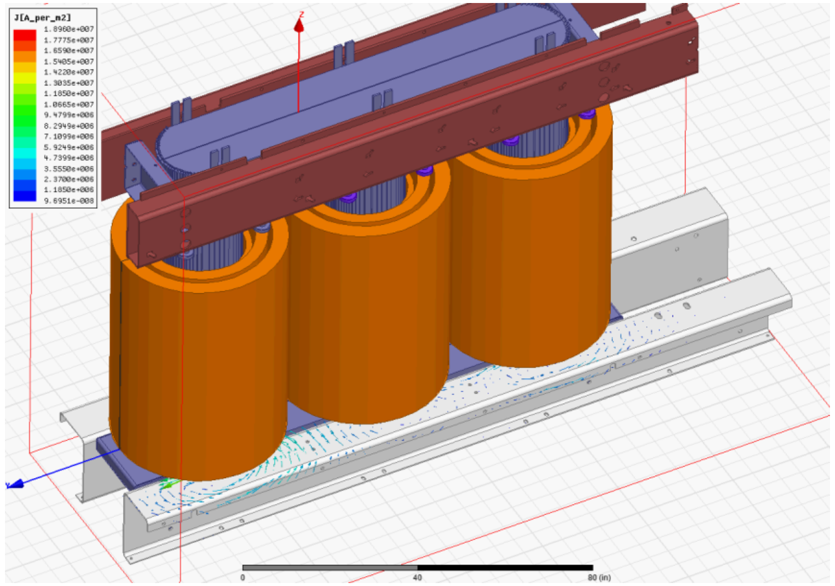
Tieplate Losses vs. Width of Tieplates
Stray Loss Reduction Outside the Windings

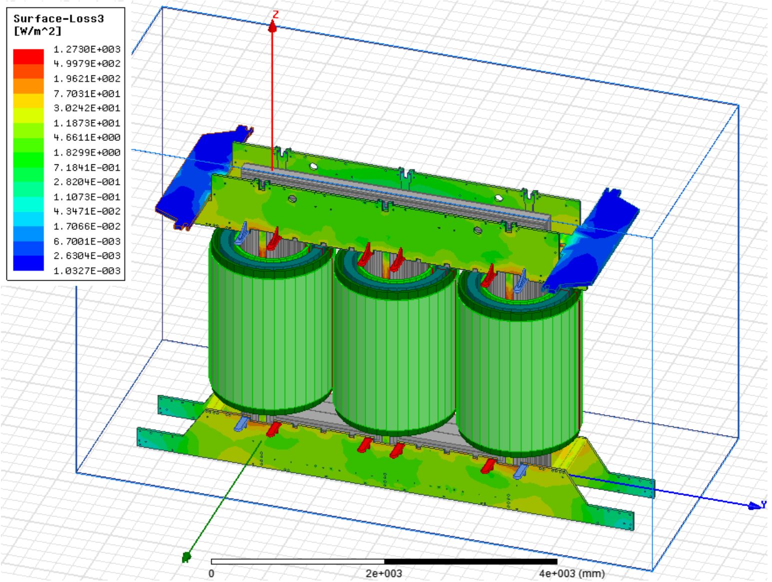


Clamp Loss and Heating

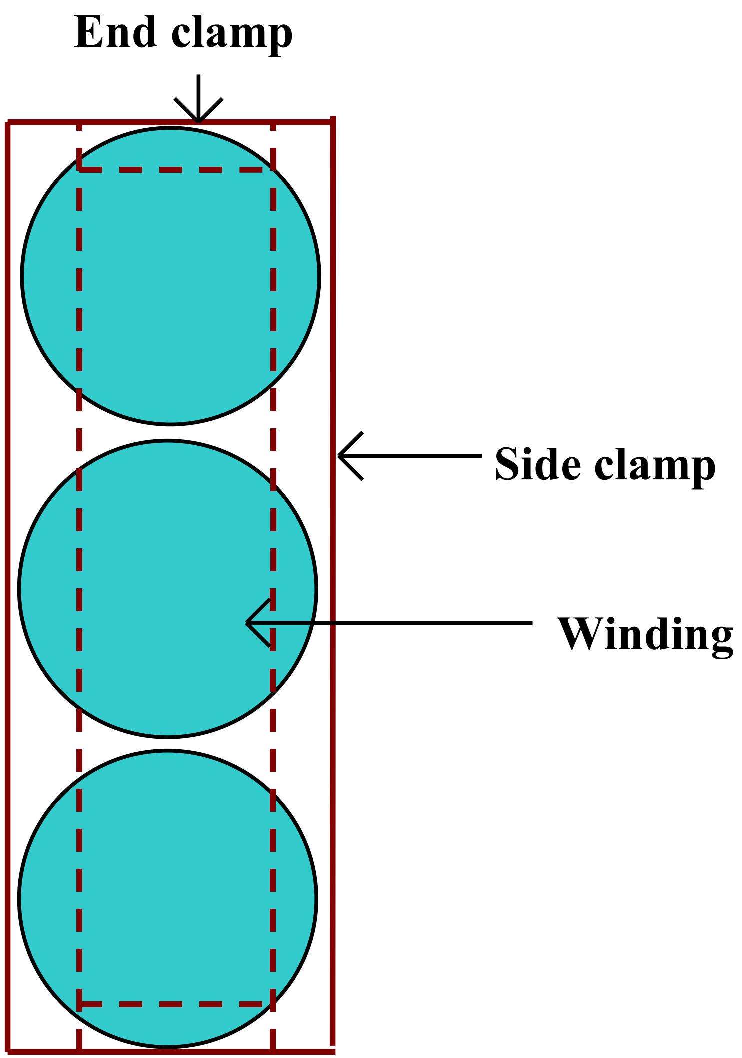






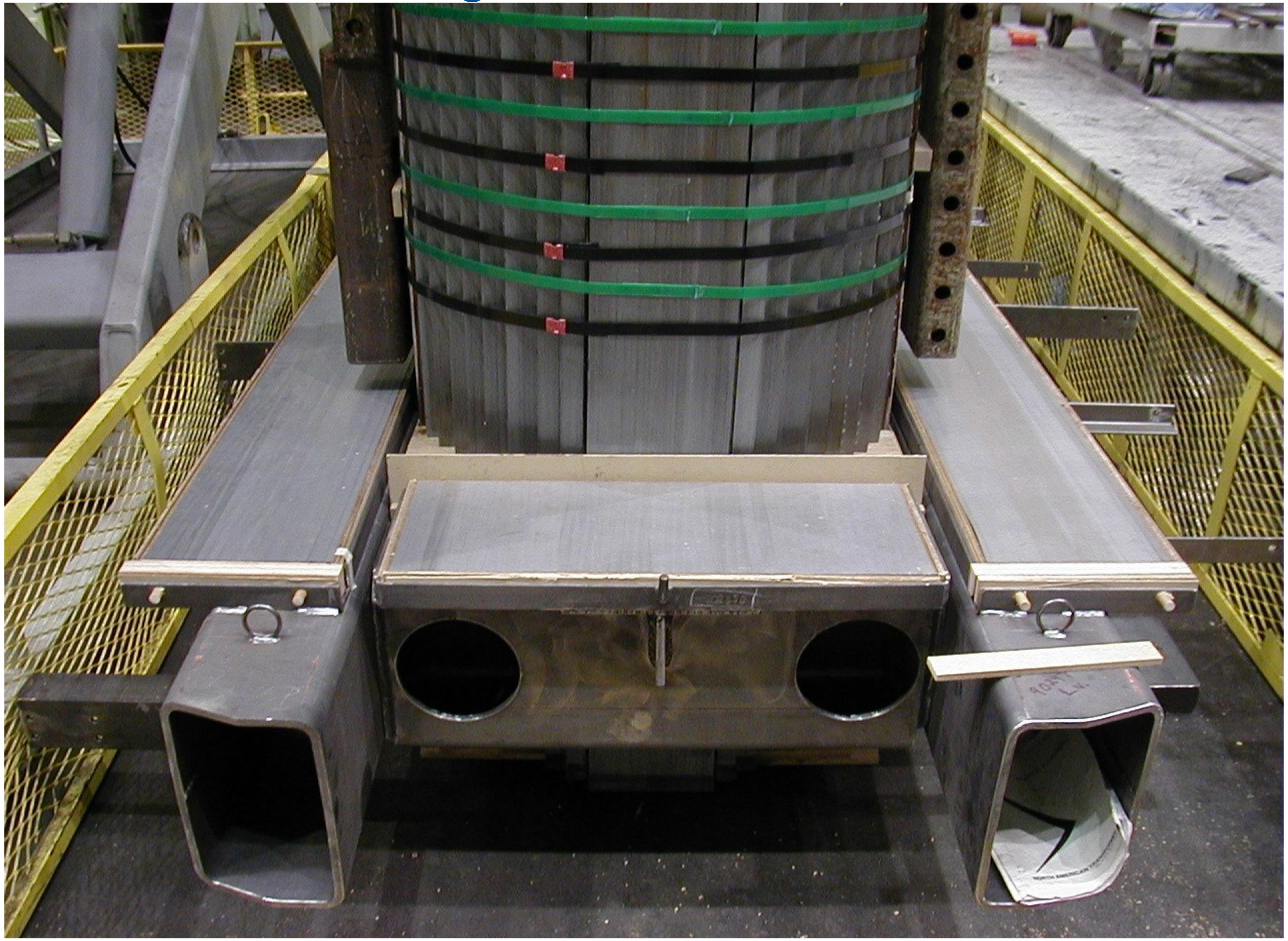


Clamp Shielding
Stray Loss Reduction Outside the Windings

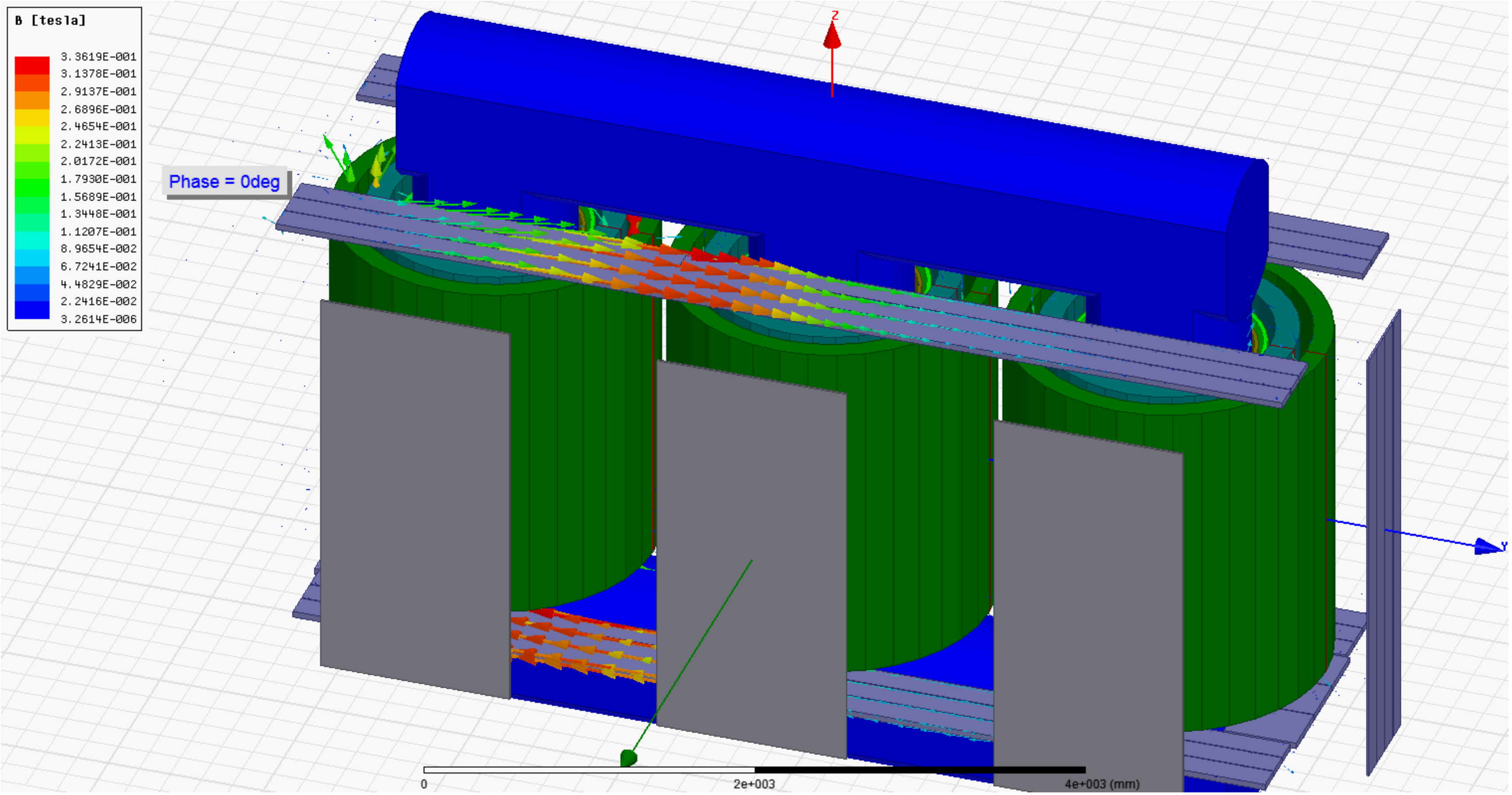


- Side clamp shunts are continuous, bridging all three phases. This allows some flux cancellation due to 3 phase effects in the clamps.
- The end clamp shunts are oriented so that flux is directed back into the core.
- Shunts are often allowed to extend beyond the clamps to reduce the possibility of flux impinging on the vertical surfaces of the clamps.
- Calculations are made for the clamp losses with / without shunts

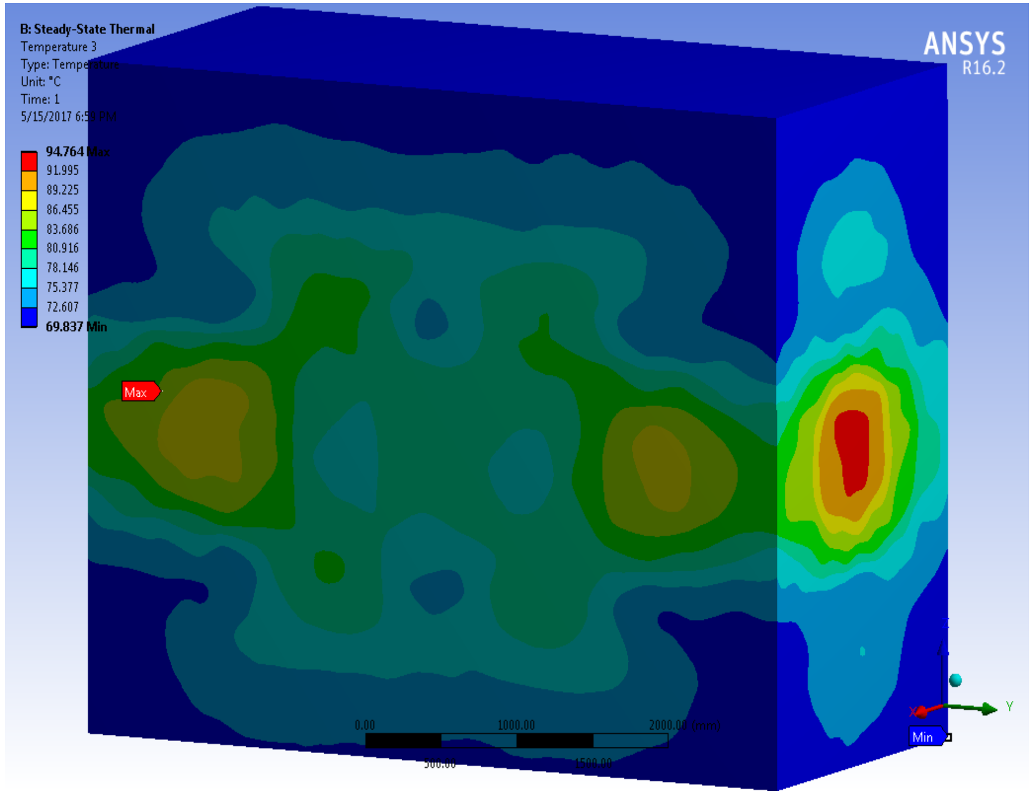
Bottom Clamp Shielding
Stray Loss Reduction Outside the Windings

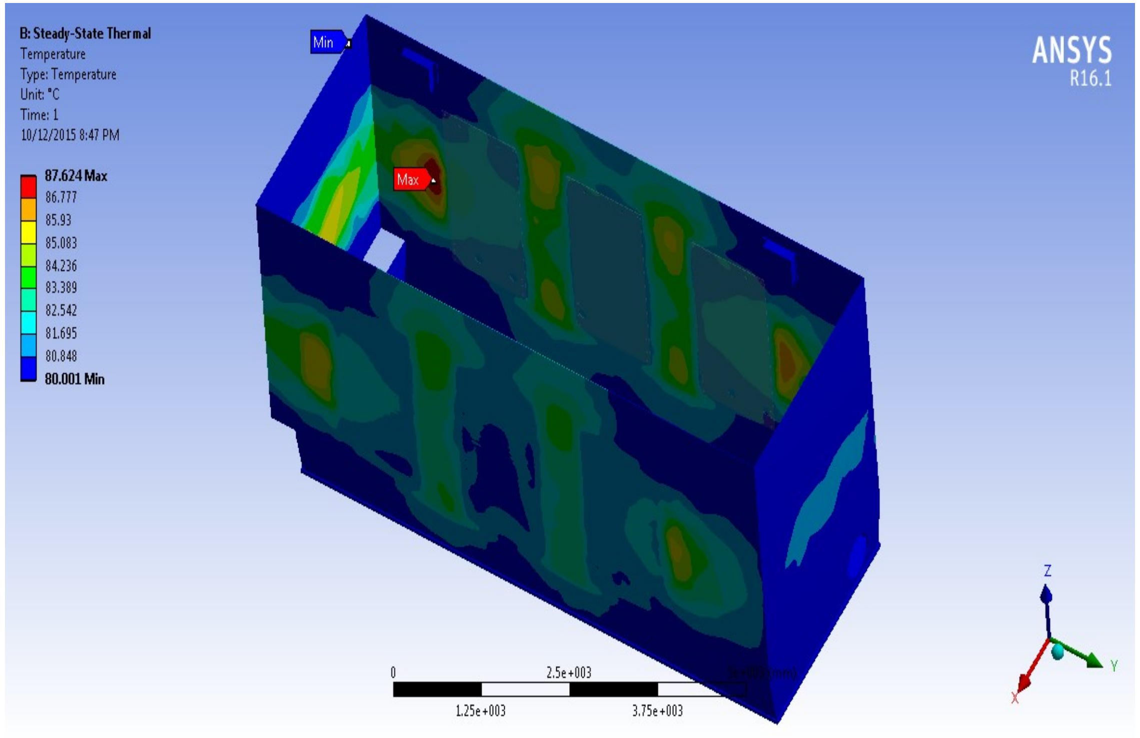


Clamp Shielding
Stray Loss Reduction Outside the Windings

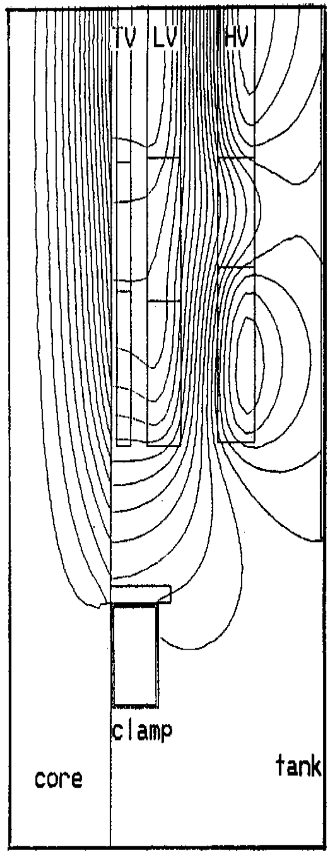


Stray Loss Heating of Tank Wall



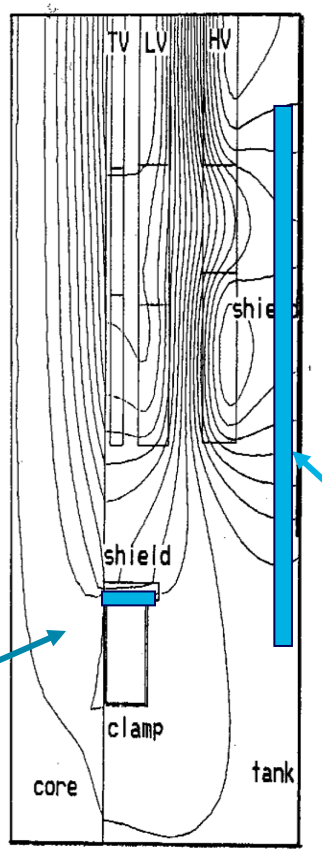


Tank / Clamp Shielding
Stray Loss Control Outside the Windings



Example
Large Auto Transformer

Core Pack Clamp Shield



Core Pack Tank Shield

No shields on tank or clamp

Tank loss = 73 W/in

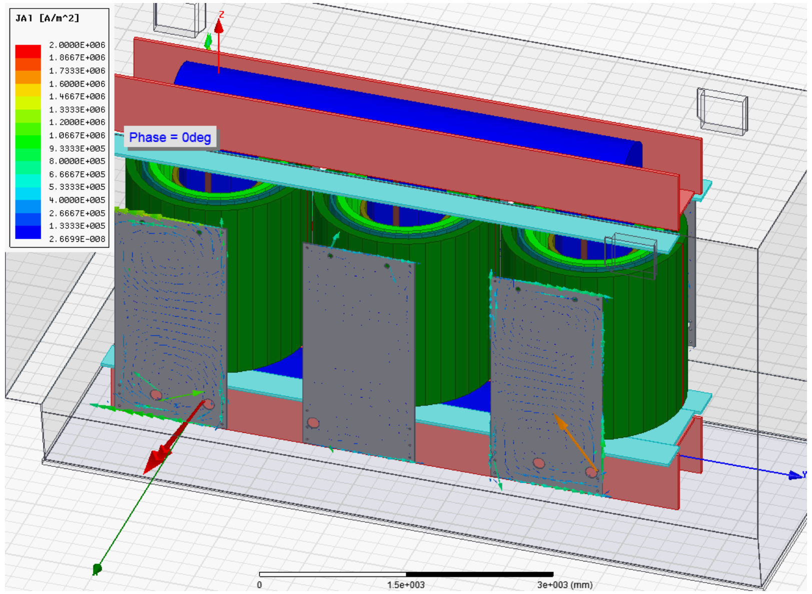
Clamp loss = 75 W/in

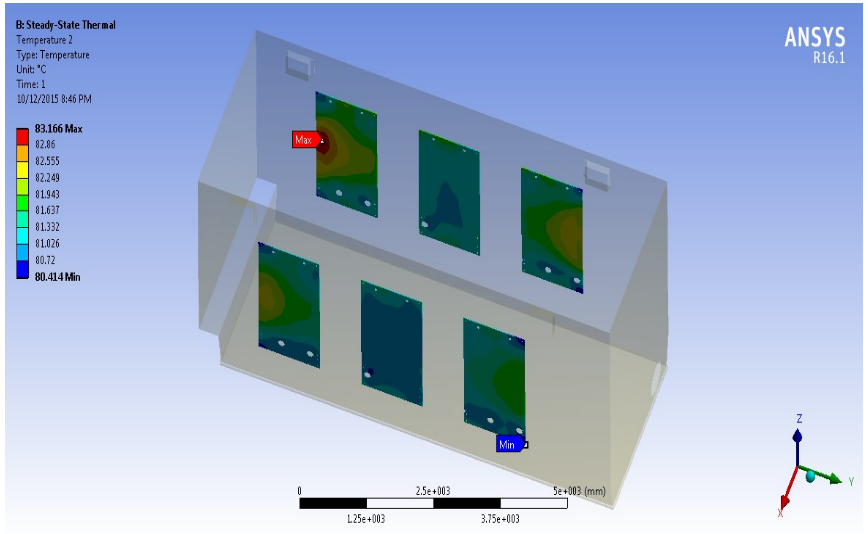
Shielded tank & clamp

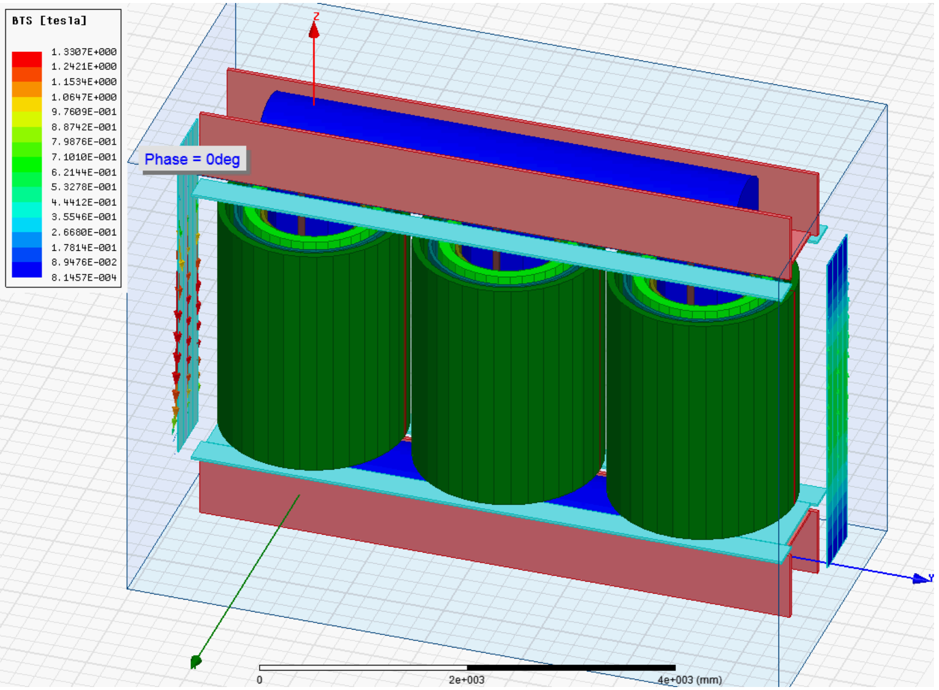
Tank loss = 3.8 W/in

Clamp loss = 2.0 W/in

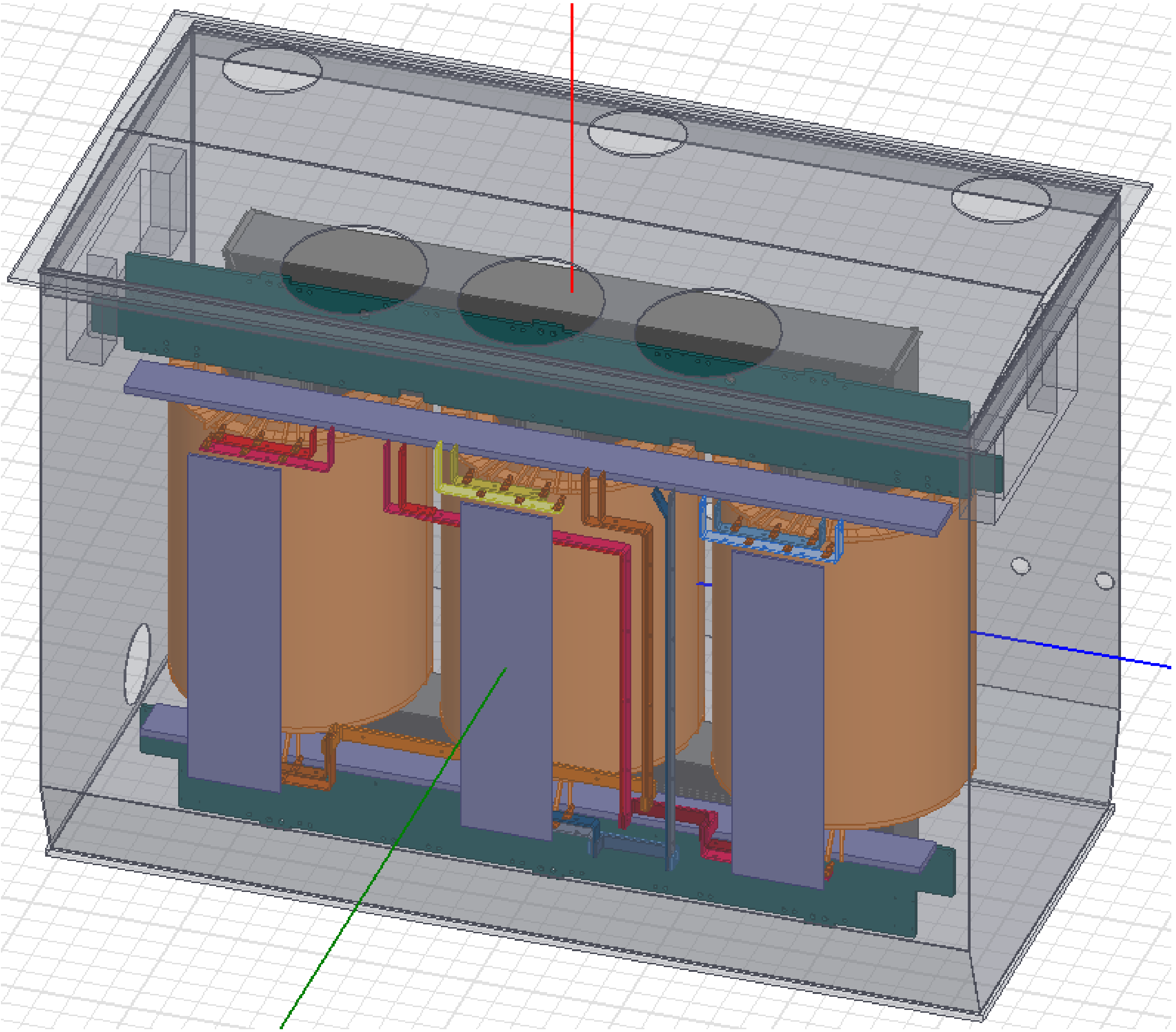
Stray Loss Control in Tank – Tank Shunts and Al Shields



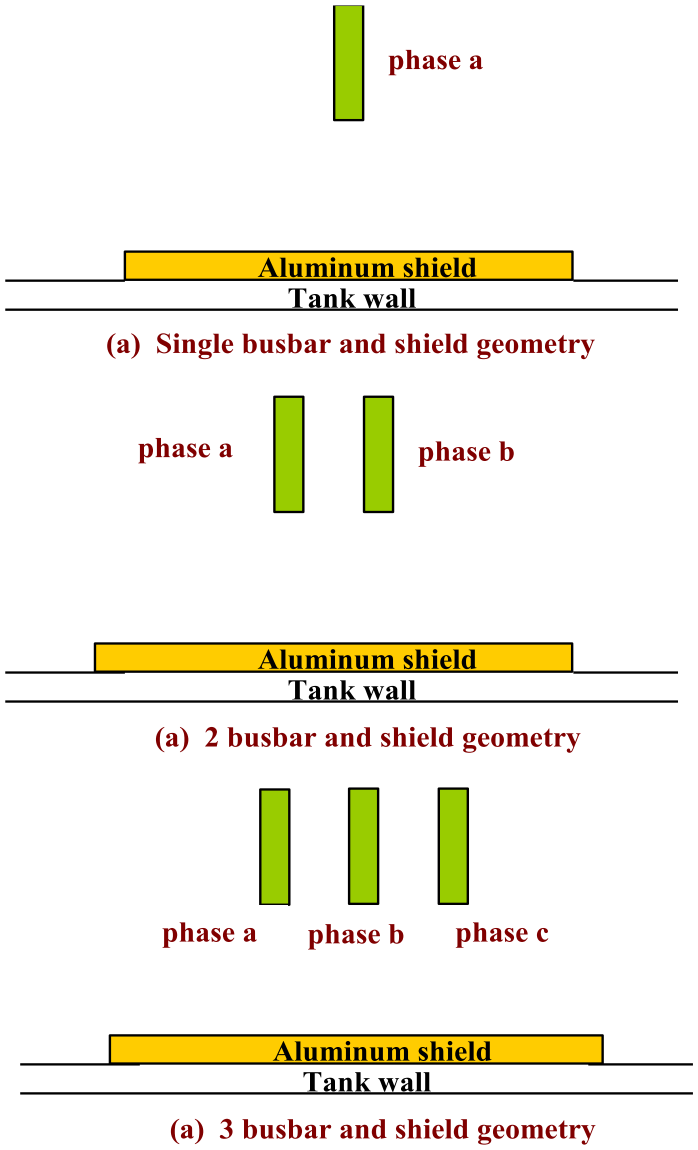




Tank Stray Loss due to Nearby Busbars Outside the Windings

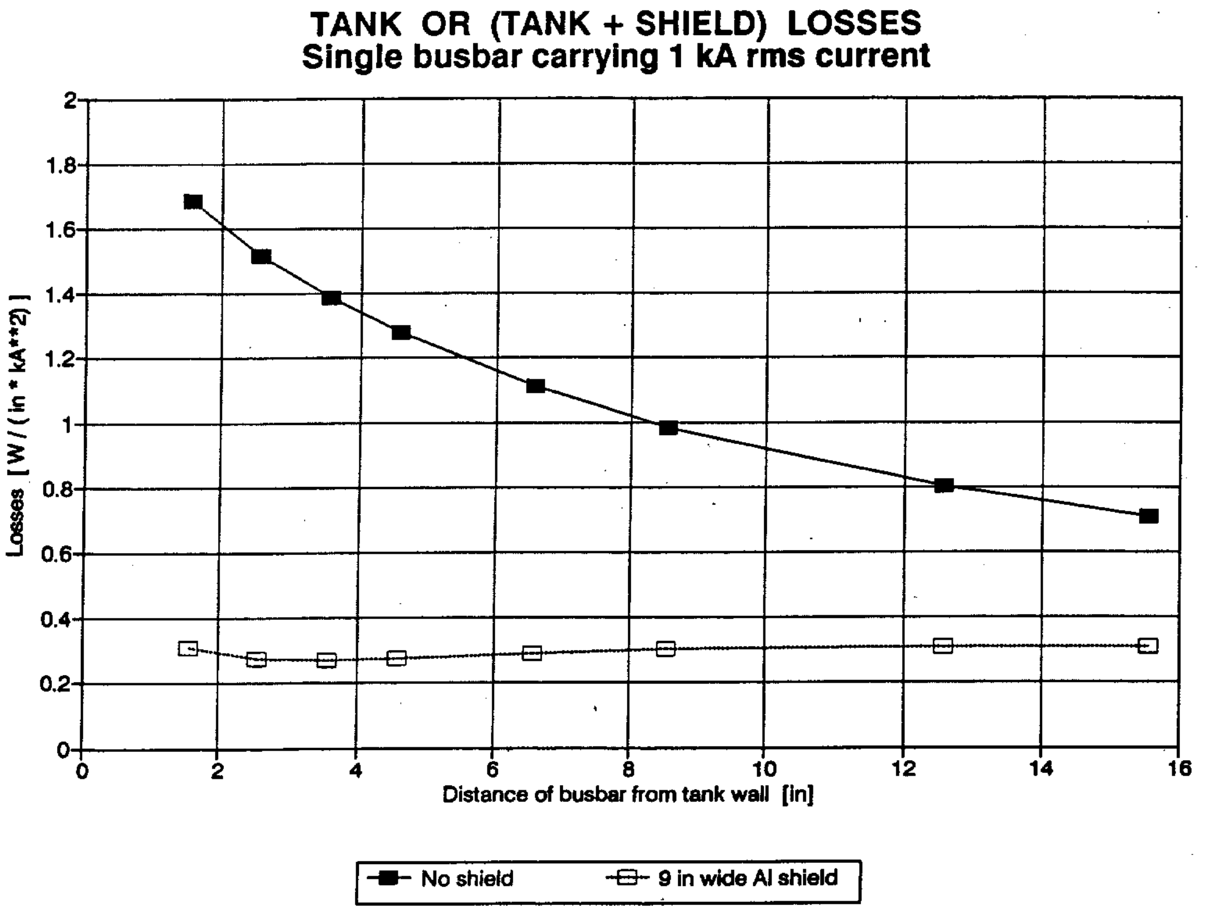


Tank Stray Loss due to Nearby Busbars Outside the Windings

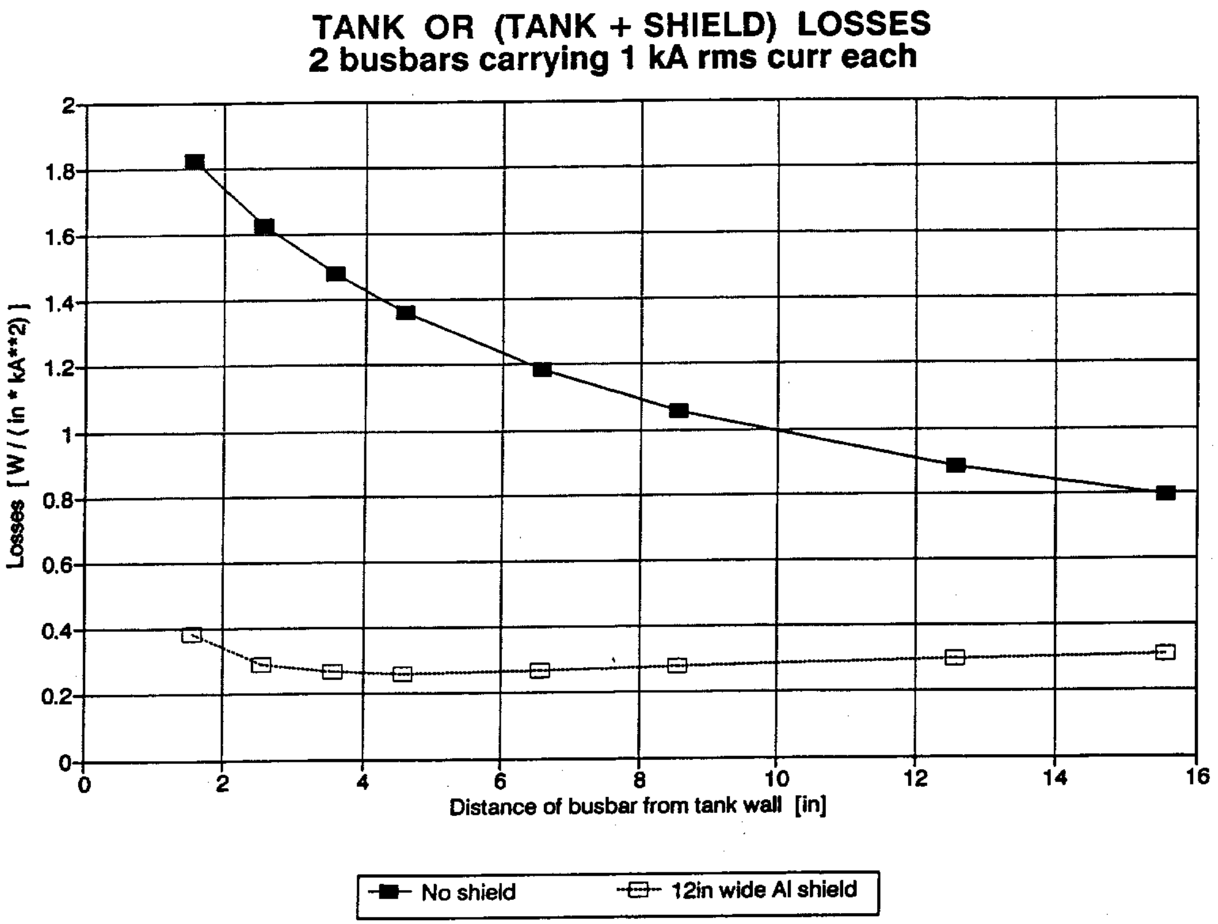


- Busbars are used when currents in the leads exceeds approx. 3000 Amps
- Busbars are parallel to the tank wall
- Aluminum or copper shields are used on tank wall adjacent to bus carrying high currents.
- Busbars are grouped together to take advantage of field cancellation, resulting in a reduced field at the tank wall.
- Thickness of shield must be > than skin depth at 60 Hz. Minimum of 1/2 inch for aluminum, 3/8 inch for copper.
- Busbars are supported at frequent intervals to withstand forces under short circuit conditions.

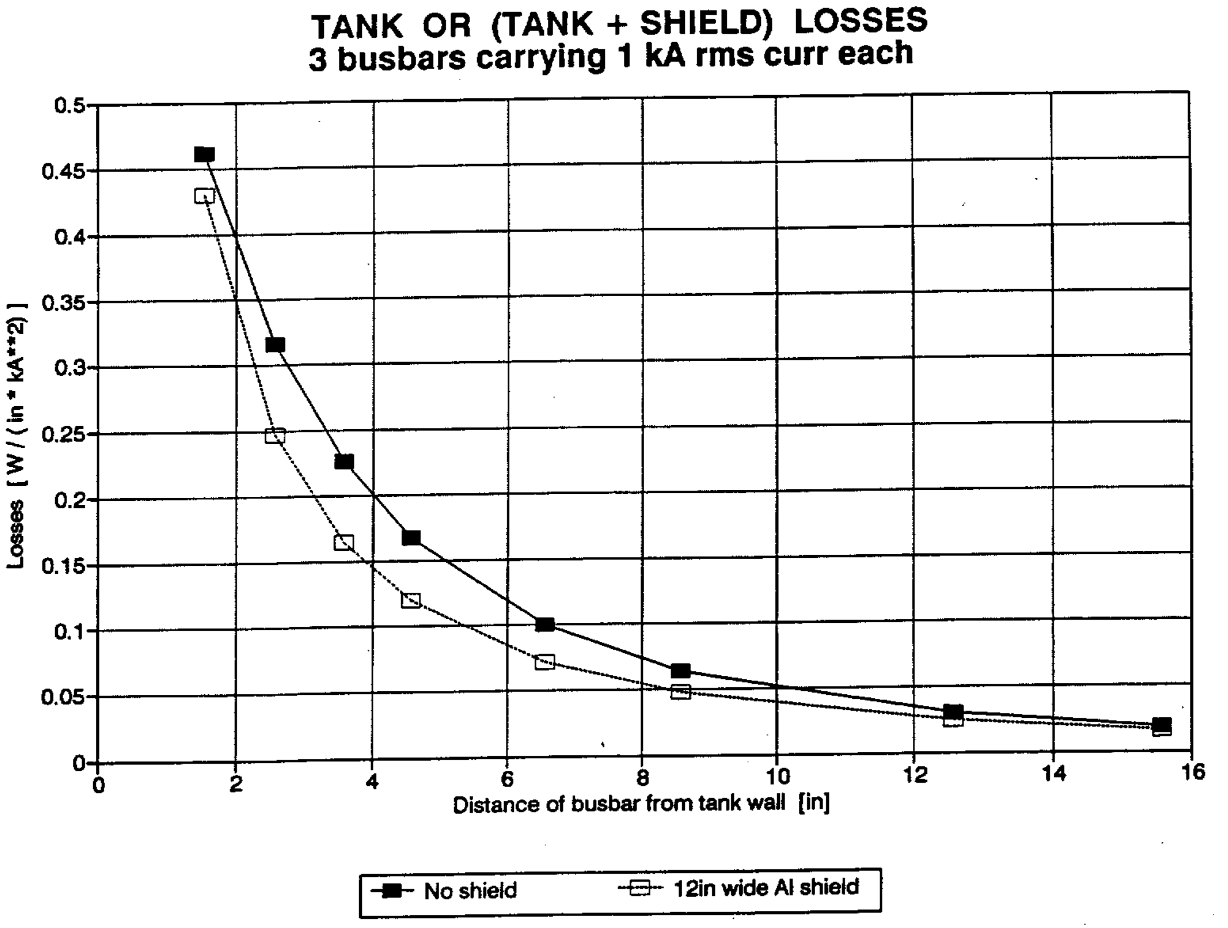
Tank Stray Loss due to a Phase A Busbar Parallel to Tank Wall – With & Without Shield



Tank Stray Loss due to Phase A&B Busbar Parallel to Tank Wall – With & Without Shield

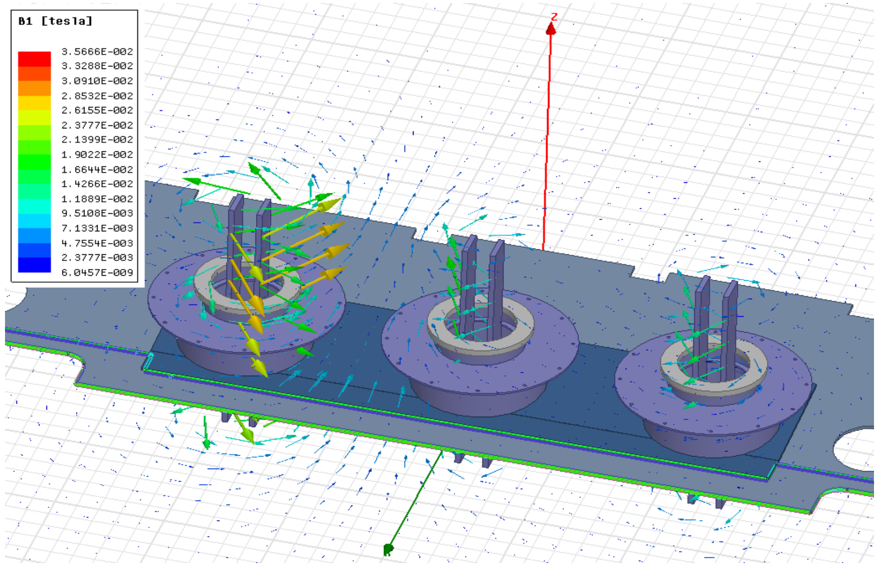


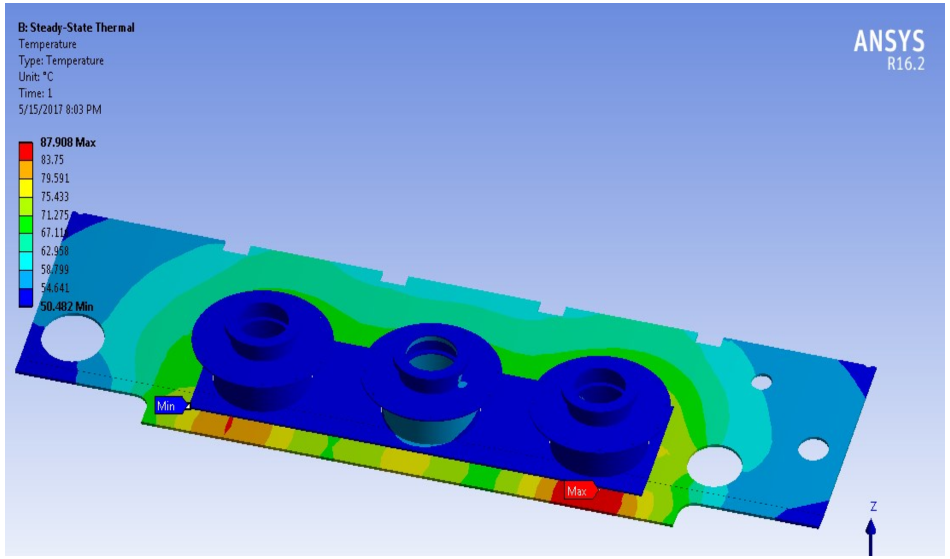
Tank Stray Loss due to Phase A, B, & C Busbar Parallel to Tank Wall – With & Without Shield

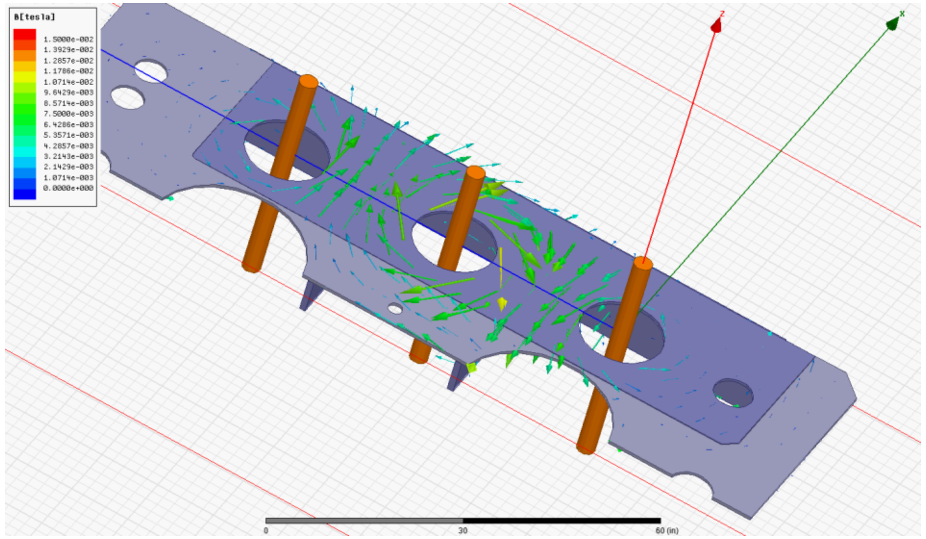


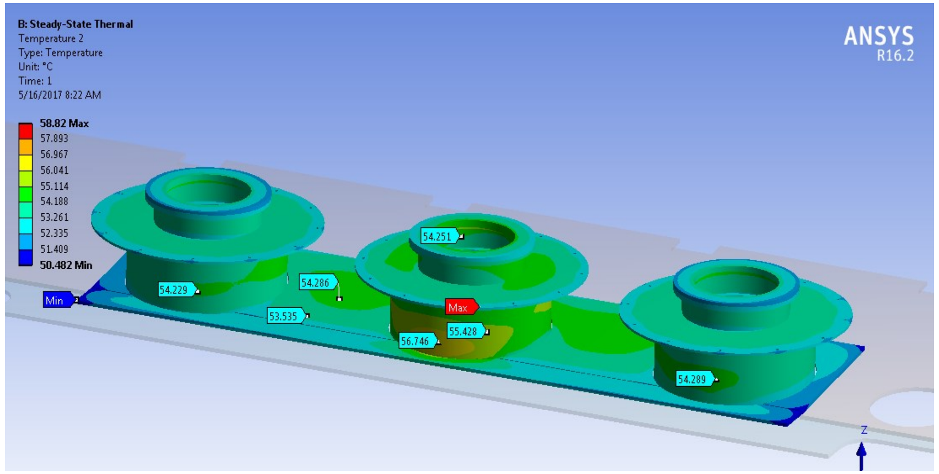
Heating of Bushing Turrets and Tank Cover due to High Current Bushing Conductors

waukesha
a prolec ge company









Conclusion

- We learned how the stray loss, which is part of the load loss, is generated by stray flux fields both internal & external to the coils.
- For reliable transformer operation, the stray loss can and must be controlled.

Methods of reducing stray loss internal to coils:

- Reduce magwire conductor size with suitable transpositions.
- Use of CTC (Continuously Transposed Cable).

Methods of reducing stray loss external to coils:

- Tieplates/End Bars – Segment steel, or use stainless.
- Tank & Clamp – Magnetic core pack shielding
- High Current Busbar/Bushings – Shield magnetic structures w/ aluminum or copper shielding, or use stainless.

Contact

Pradeep Ramaswamy
Design & Development Engineer

Prolec-GE Waukesha, Inc.
Waukesha, WI
pradeep.ramaswamy@prolec.energy
T 262-446-8530

www.waukeshatransformers.com