Transformers 101

Transformer Regional Technical Seminar

Livermore CA

September 24, 2024

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Vivek Bhatt
Mechanical Engineering Manager

Vivek joined North American Transformer in 1996 which became part of Prolec GE Waukesha in 1999. He has over 30 years of experience in the fields of design and testing of medium and large power transformers with ratings up to 400 MVA, 345kV class and 1175kV BIL. Vivek holds a BTech degree in electrical engineering from KNIT in India.

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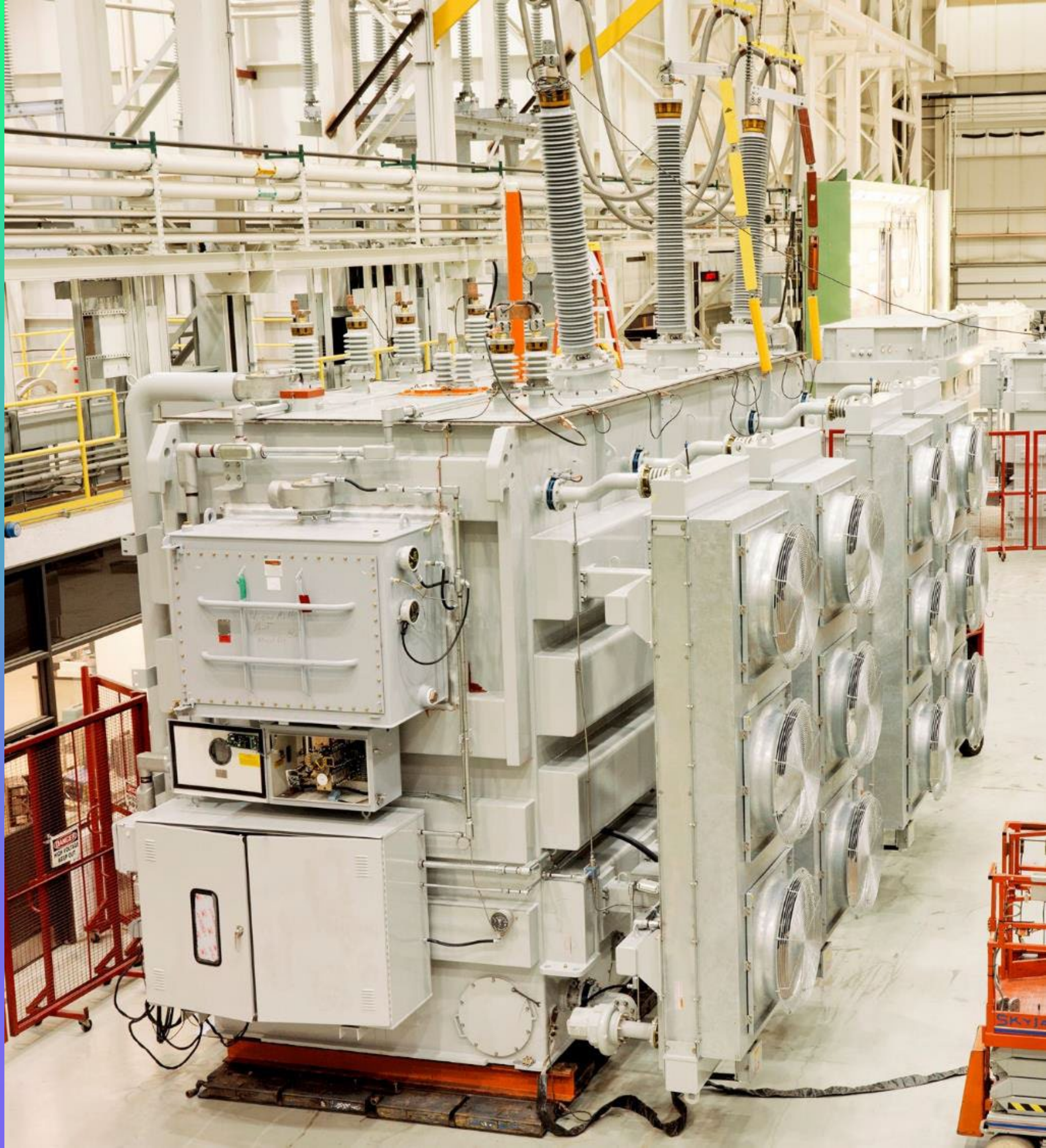

Agenda

- Market Dynamics & Outlook
- The History of the Transformer
- Review transformers: How they work (textbook vs reality)
- How do we build a reliable transformer – Virtual Tour
- Specification requirements and Accessories
- Types of Core & Core Parameters
- Types of Windings & Conductors
- Insulating Materials
- Design Process
- Testing

Market Dynamics & Outlook

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Key Market Drivers

The U.S. is undergoing a significant energy transition driven by decarbonization efforts and digitalization:

- Infrastructure Investment and Jobs Act (IIJA) & Inflation Reduction Act (IRA) funds continue to bolster the US energy transition.

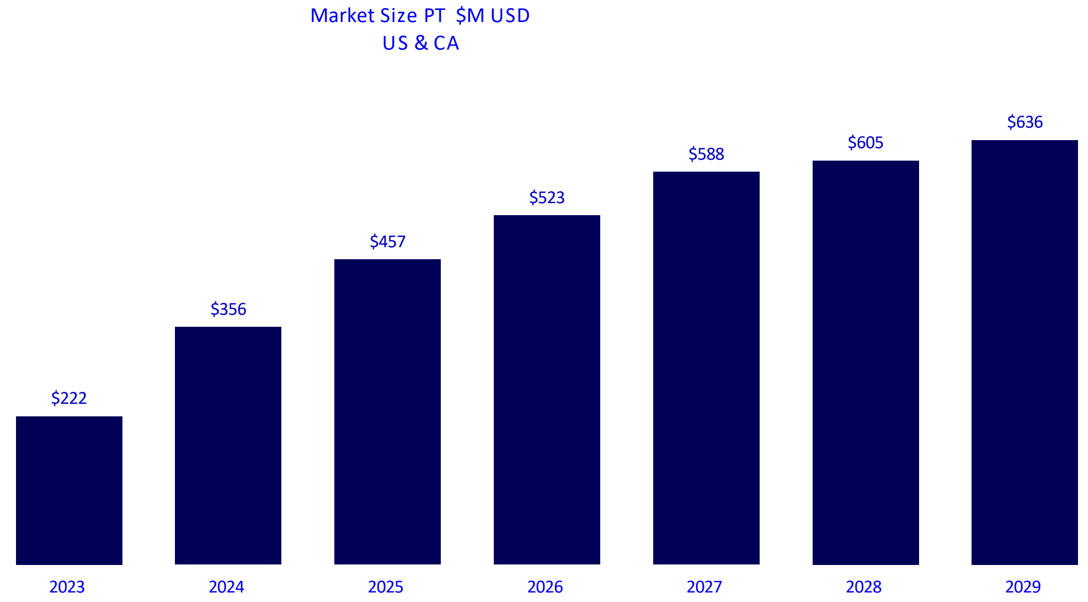
- Renewables growth continues in solar, wind, and battery storage
  - The percentage of renewable generation will jump from 22% in 2022 to 23% in 2023 and 25% in 2024, while nuclear power's share will hold at 19%.
  - Due to inflationary pressures the US offshore wind power capacity under contract dropped 18% in the third quarter of this year.
- Grid interconnects expected to drive increases in transmission investment
  - US Utilities need $80 - $100bn in transmission investment to meet IRA goals.
  - US Merchant Transmission developers have found success by sidestepping one of the most difficult challenges. In lieu of any effective joint interregional planning, merchant companies are filling the void with individual power suppliers that subscribe to the line's transmission capacity.

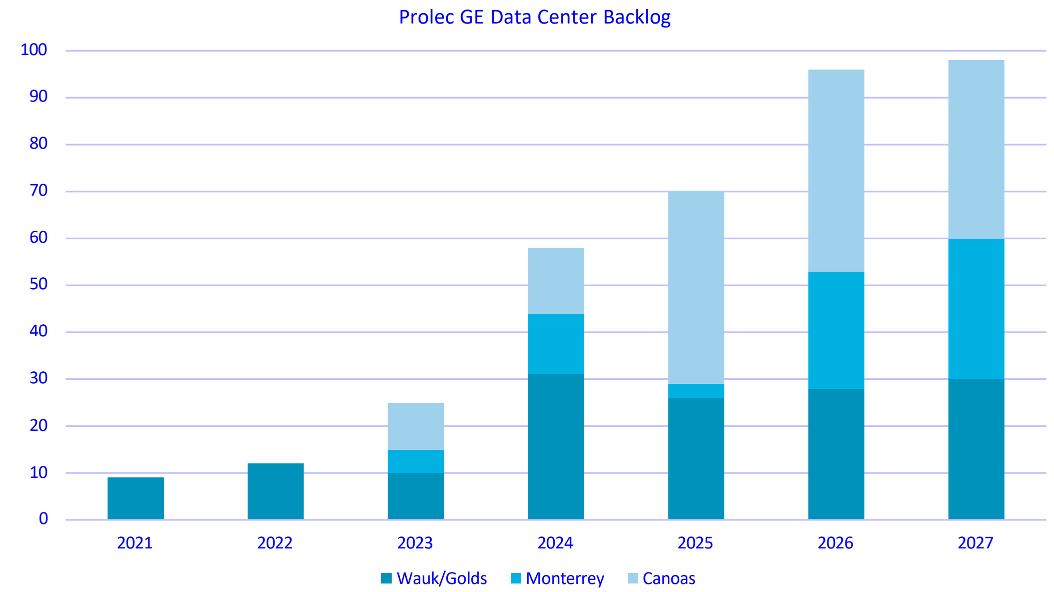
- Data center expansion due to increase in digitalization (AI and Cloud-based storage)
  - US has the largest datacenter market in the world, Electric utilities that serve it point to it a "growth machine“.
- Asset aging and replacement
  - Most of the U.S. electric grid was built in the 1960s and 1970s
  - In addition to investments being made in support of growth and expansion it is estimated US utilities are investing a combined $20-$25bn per year in support of aging infrastructure and assets.

- Record demand is rapidly consuming capacity and pushing lead times for power transformers out 3 to 4 years or more.

- Supply chain constraints related to labor and material availability is requiring order timing at a minimum of 52 weeks prior to shipment.

Data Center Market





- Estimated CAGR of 19% from 2023-2029 for power transformer demand for data centers in US & Canada
- Driven by rapid surge in AI development from tech firms such as Amazon, Apple, Google, Meta and Microsoft
- Prolec GE's data center backlog is growing at a CAGR of 49% from 2021-2027
  - Significant increases from Canoas beginning in 2025 and from Monterrey in 2026
- Continuing trend of growing MVA ratings, which further stresses LP/EHV capacity

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The History of the Transformer

- Ottó Bláthy, Miksa Déri, Károly Zipernowsky of the Austro-Hungarian Empire First designed and used the transformer in both experimental, and commercial systems.
- Later on Lucien Gaulard, Sebstian Ferranti, and William Stanley perfected the design
- The property of induction was discovered in the 1830's but it wasn't until
- 1886 that William Stanley, working for Westinghouse built the first reliable commercial transformer.
- His work was built upon some rudimentary designs by the Ganz Company in Hungary (ZBD Transformer 1878), and Lucien Gaulard and John Dixon Gibbs in England.

The History of the Transformer

Transformer - a device that transfers electrical energy from one circuit to another circuit using inductively coupled conductors.

In other words by putting two coils of wire close together while not touching,

the magnetic field from the first coil called the primary winding effects the other coil (called the secondary coil).

This effect is called "inductance". Inductance was discovered by Joseph Henry and Michael Faraday in 1831.

Current & Magnetic Field Relationships

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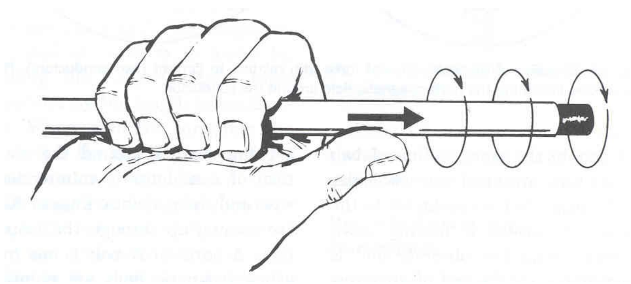
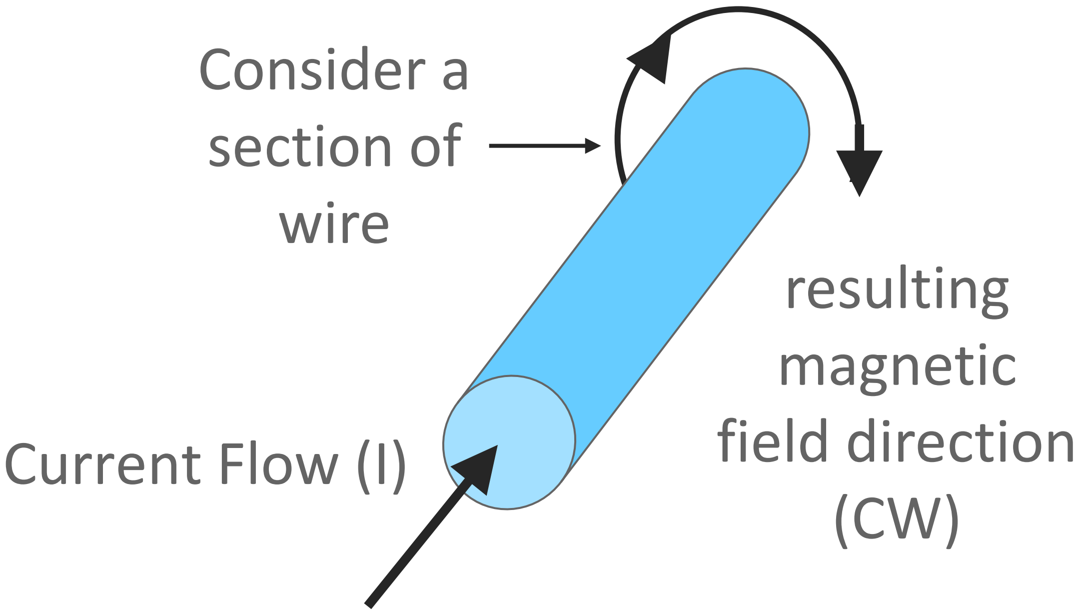
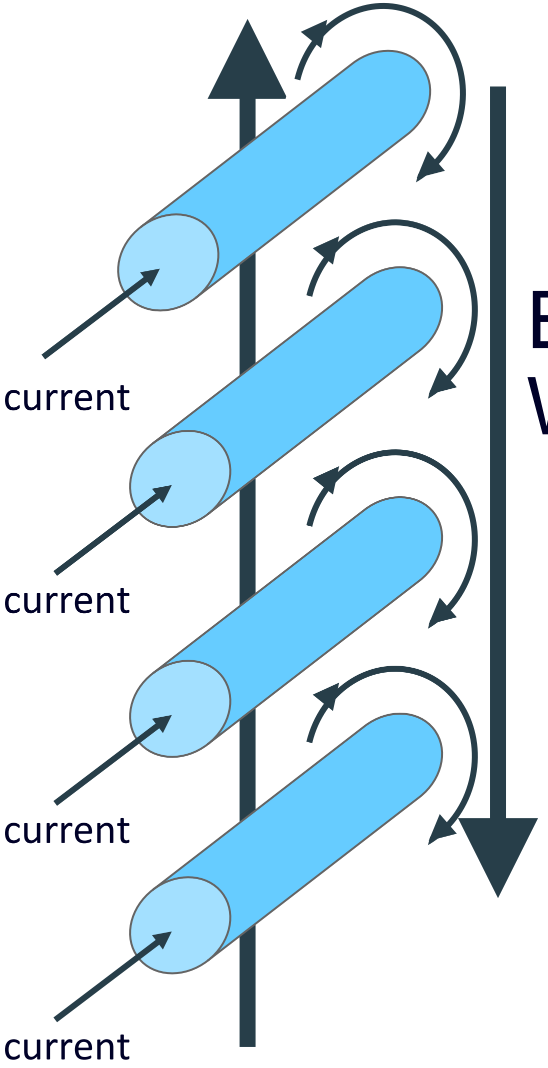


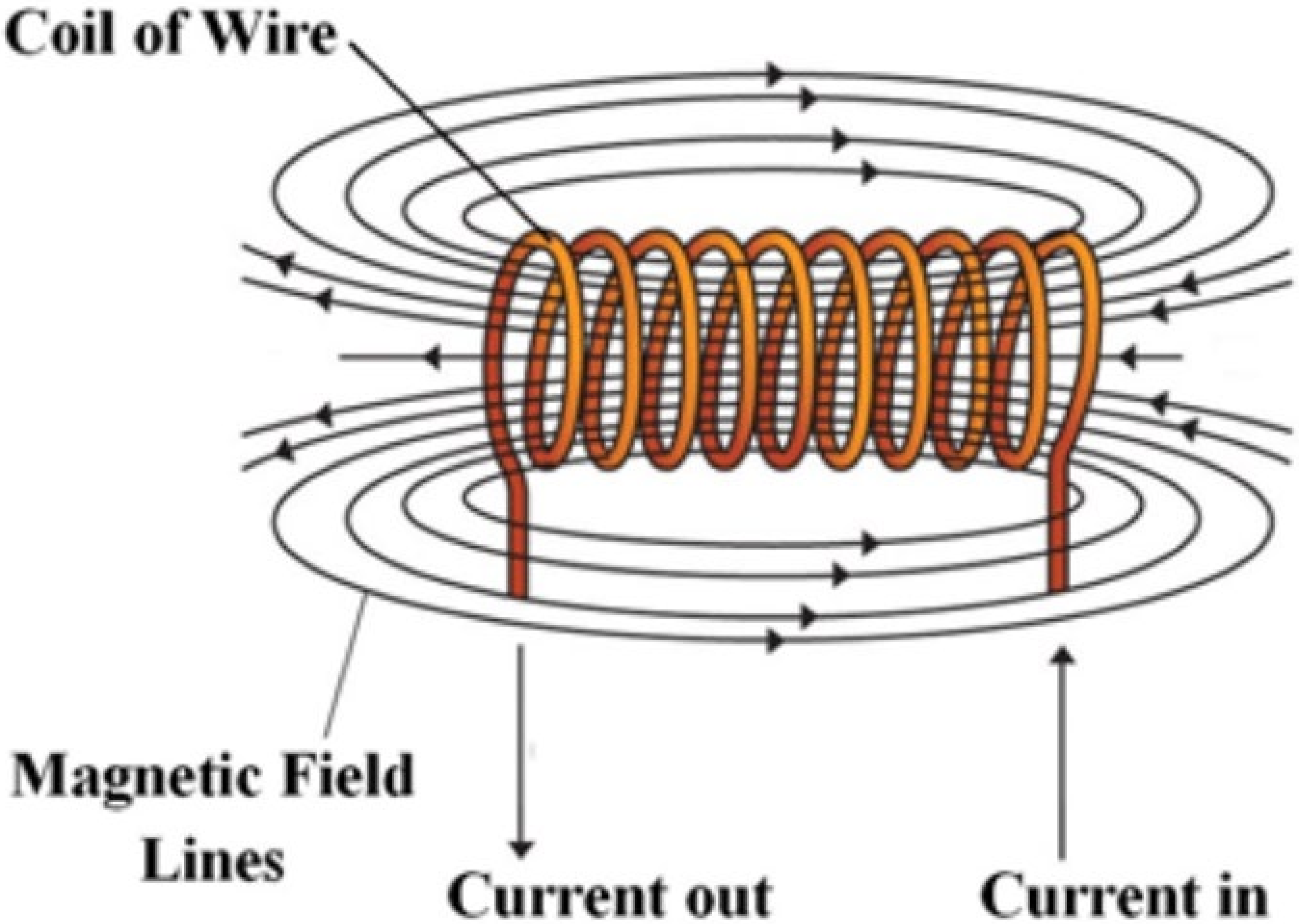
Right hand rule





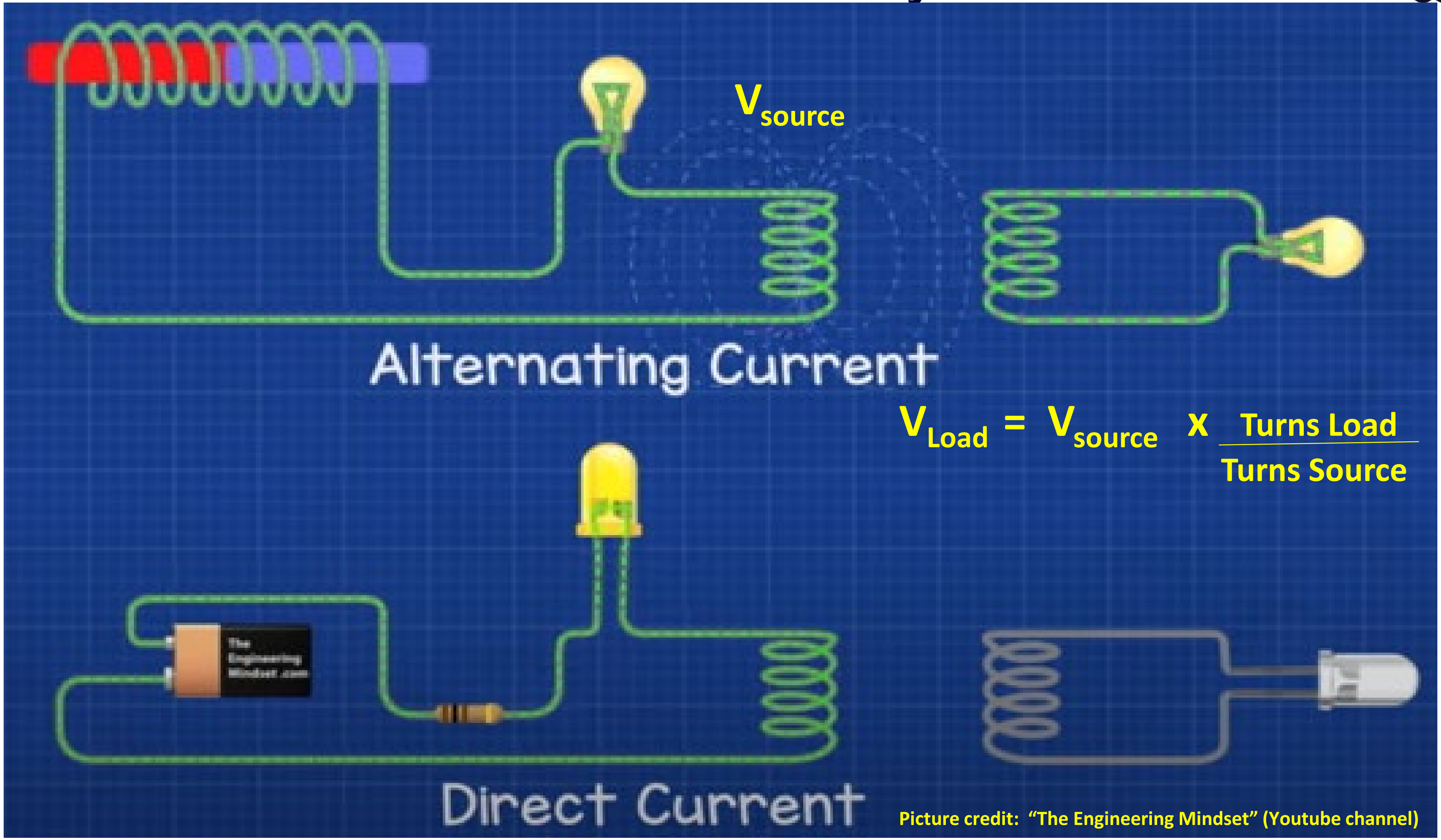
Effect of Many Wires Together

Effect of putting the wire into a coil



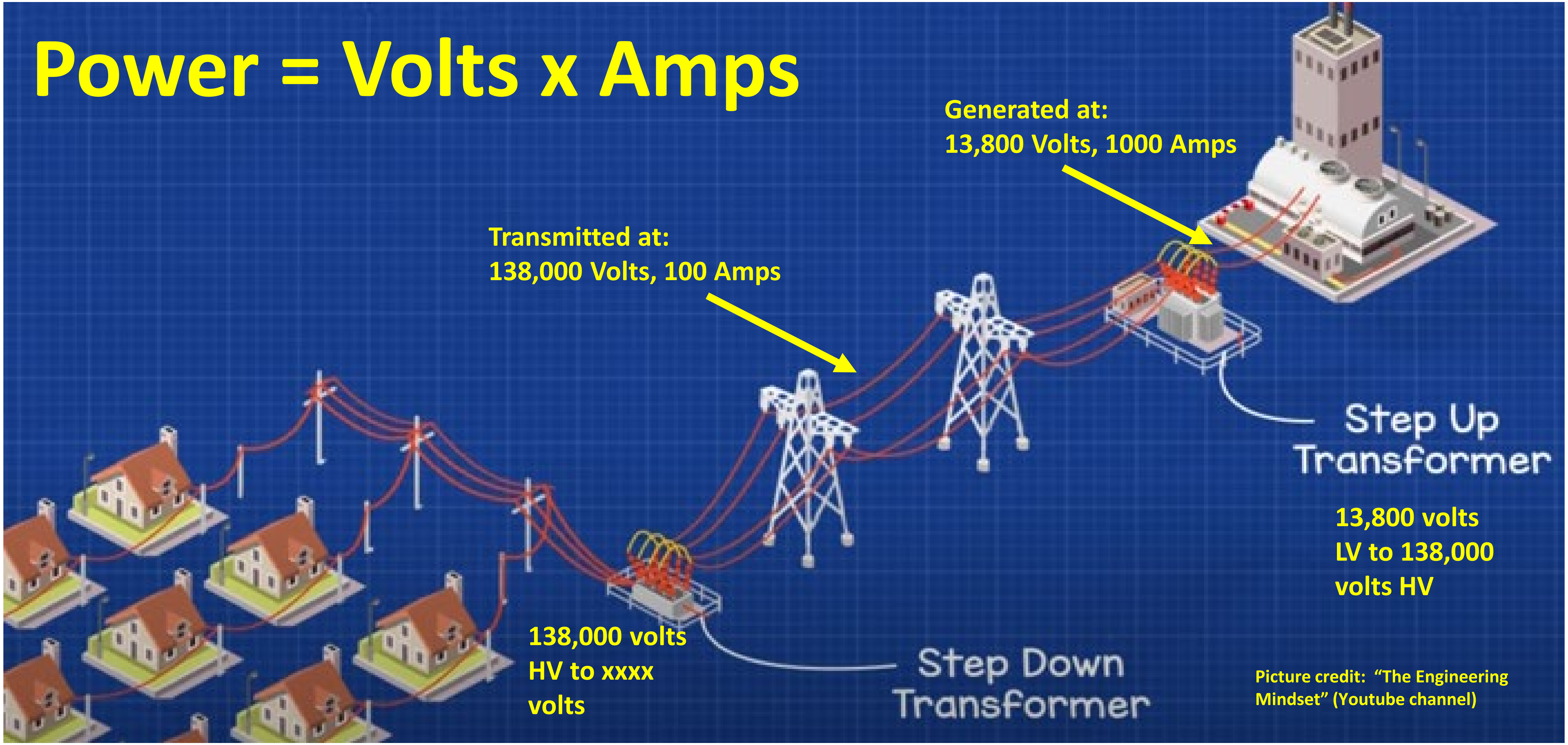
Picture credit:
www.researchgate.net

AC vs DC effects on secondary circuit

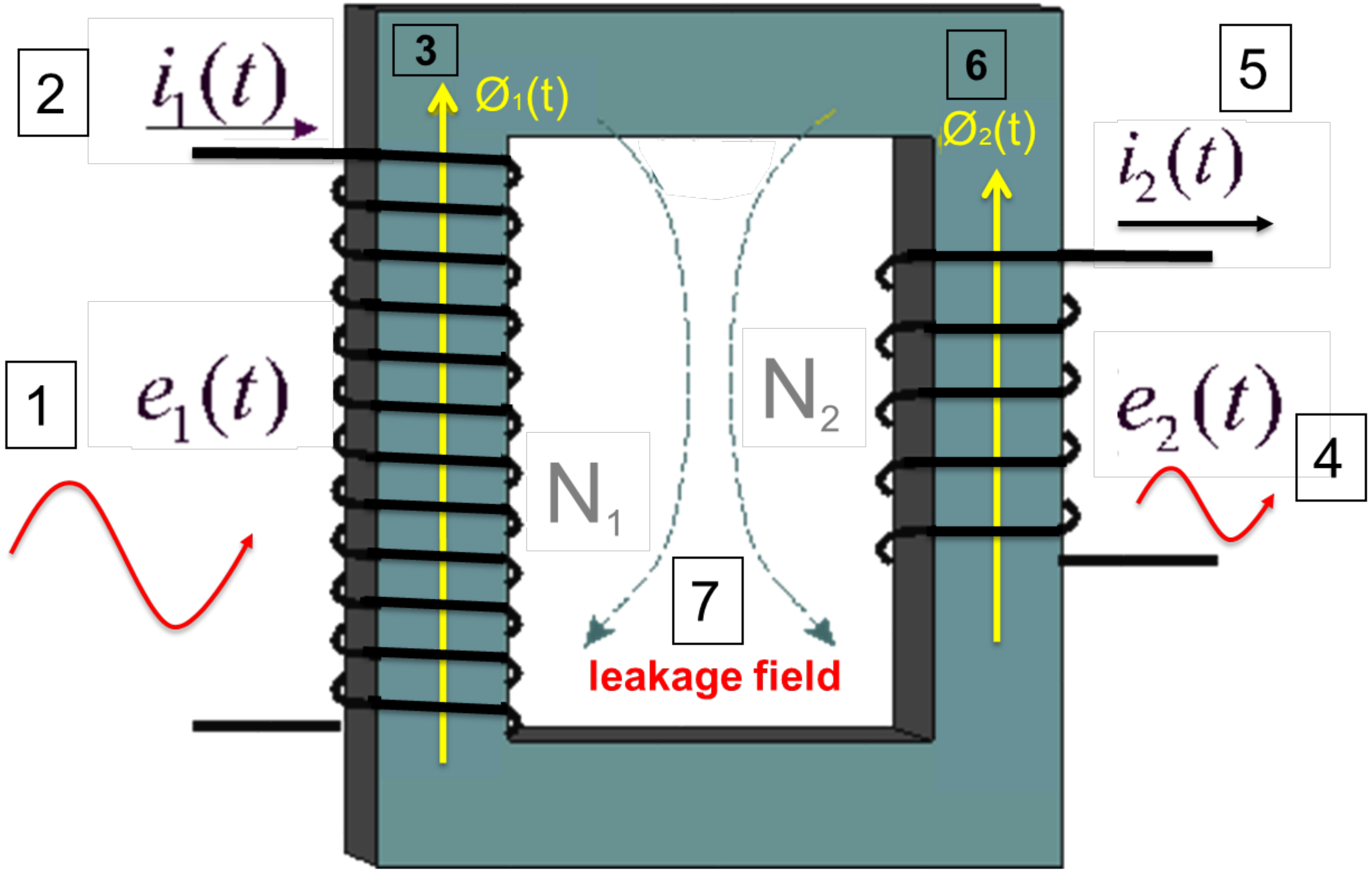


Picture credit: "The Engineering Mindset" (Youtube channel)

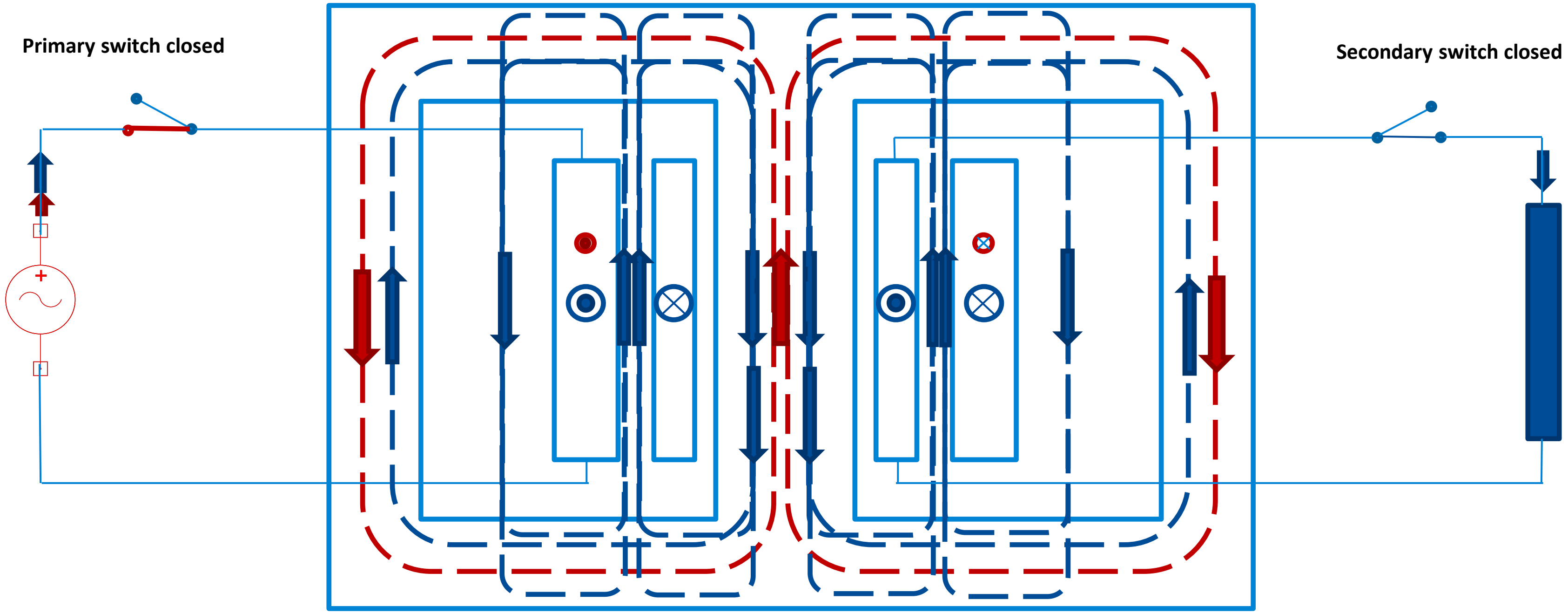
Basic Power Transmission

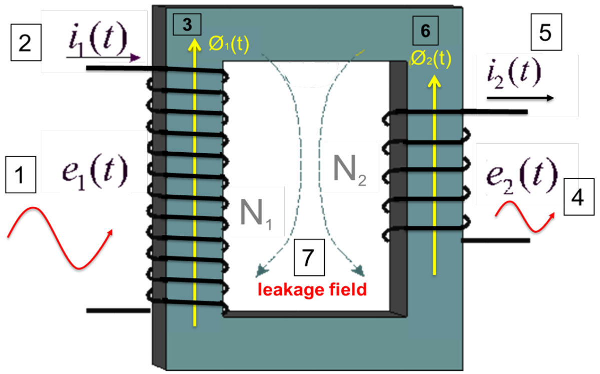


Textbook Transformer (step by step)



Transformer Operation step-by step





EMF Equation of a Transformer

Applied voltage $v_1 = N_1 \frac{d\phi}{dt}$

Counter emf $e_1 = -N \frac{d\Phi}{dt}$ volts

As the applied voltage is sinusoidal ,that is

$v_1 = v_{1\mathrm{m}\ \mathrm{Sin}\ 2\pi f t}$

$\phi = \phi_m \,\mathrm{Sin}\, 2\pi f t$

$\frac{d\Phi}{dt} = \phi_m \cos 2\pi f t \; X 2\pi f$

$e_1 = -N_1 \phi_m \cos 2\pi f t \; X 2\pi f$

RMS value of counter emf

$$\mathrm{E_1} = \frac{2\pi}{\sqrt{2}} \mathrm{fN_1 \phi m}$$

$$\mathrm{E_1} = 4.44\mathrm{fN_1 \phi m}$$

$$\mathrm{E_1} = 4.44\mathrm{fN_1 Bm\ A}$$

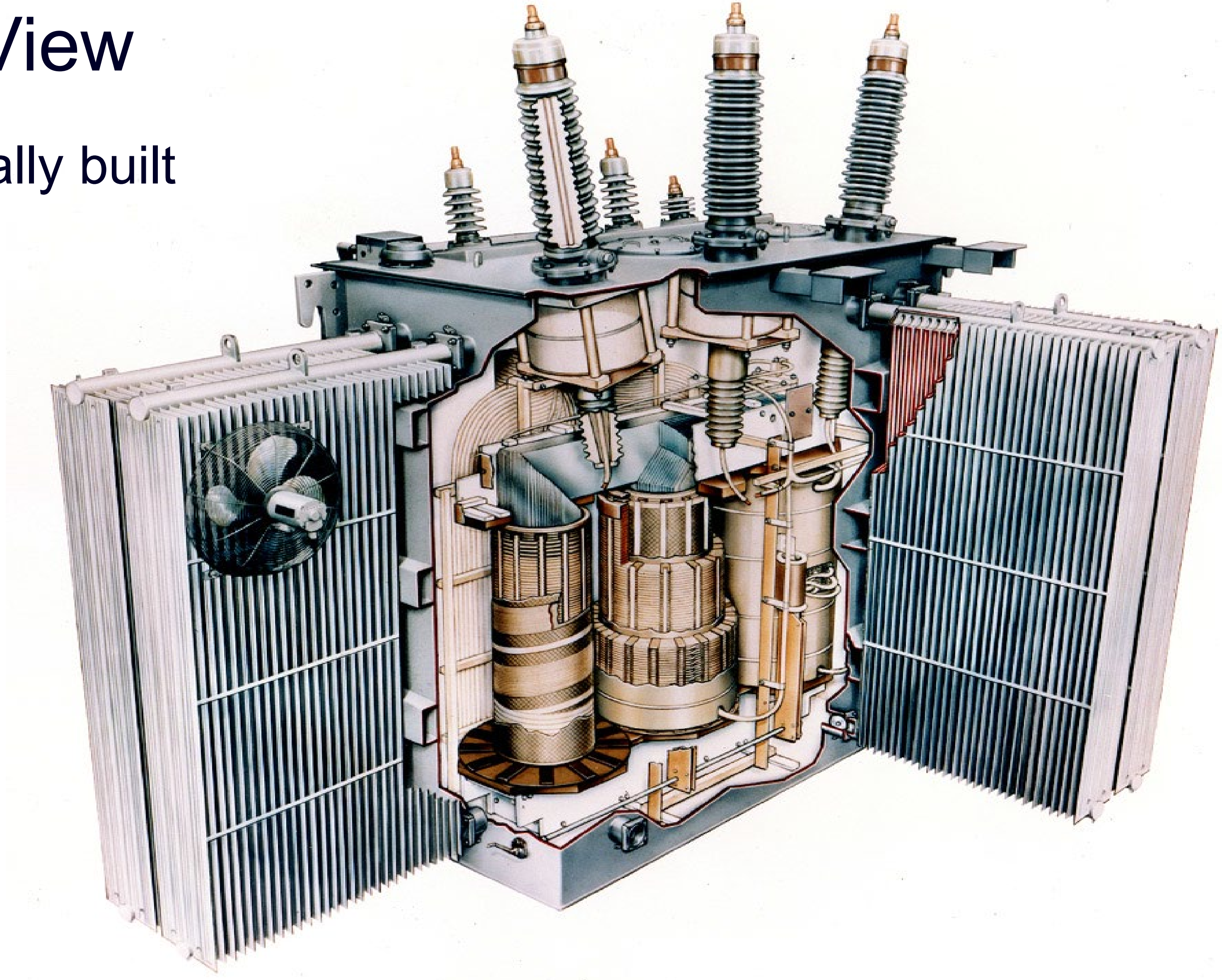
$$\mathrm{E_2} = 4.44\mathrm{fN_2 Bm\ A}$$

For an ideal transformer

$V_1 = E_1$ and $V_2 = E_2$

Cutaway View

How one is really built



Virtual Factory Tour

Specification requirements and Accessories

Requirements by Specification

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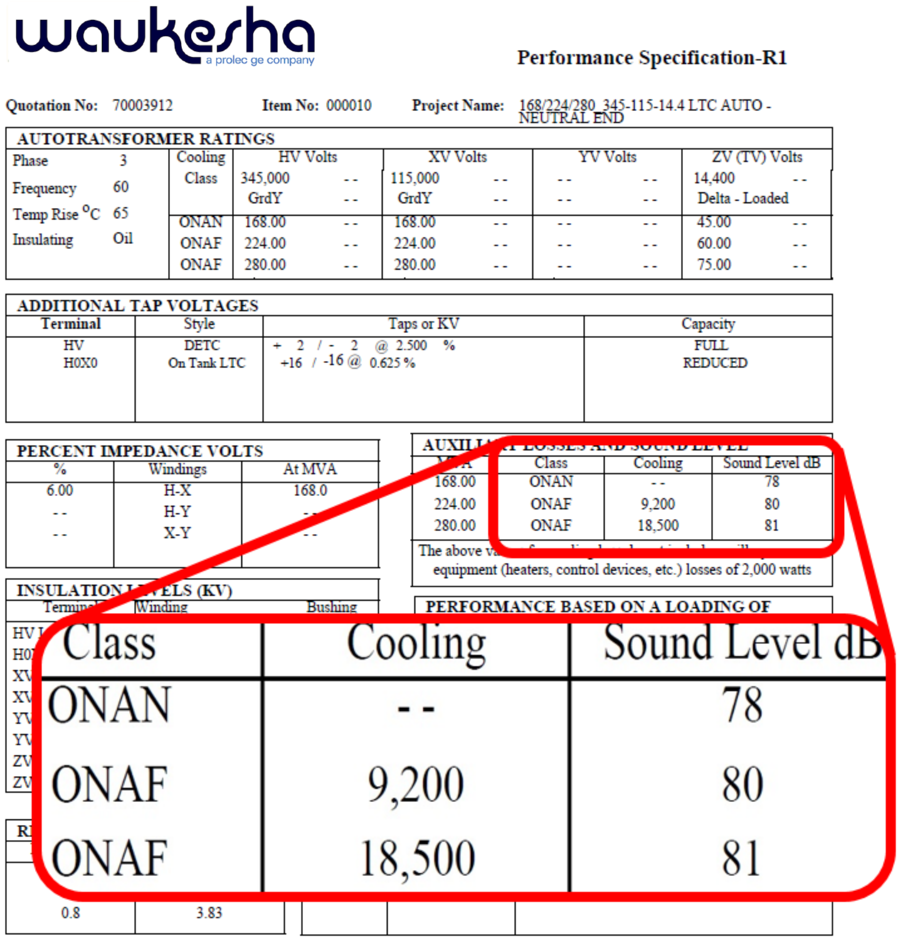

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Performance Specification-R1

Quotation No: 70003912 **Item No:** 000010 **Project Name:** 168/224/280 345-115-14.4 LTC AUTO - NEUTRAL END

AUTOTRANSFORMER RATINGS

		Cooling Class	HV Volts		XV Volts		YV Volts		ZV (TV) Volts	
Phase	3		345,000	- -	115,000	- -	- -	- -	14,400	- -
Frequency	60		GrdY	- -	GrdY	- -	- -	- -	Delta - Loaded	
Temp Rise °C	65	ONAN	168.00	- -	168.00	- -	- -	- -	45.00	- -
Insulating	Oil	ONAF	224.00	- -	224.00	- -	- -	- -	60.00	- -
		ONAF	280.00	- -	280.00	- -	- -	- -	75.00	- -

ADDITIONAL TAP VOLTAGES

Terminal	Style	Taps or KV	Capacity
HV	DETC	+ 2 / - 2 @ 2.500 %	FULL
H0X0	On Tank LTC	+16 / -16 @ 0.625 %	REDUCED

PERCENT IMPEDANCE VOLTS

%	Windings	At MVA
6.00	H-X	168.0
- -	H-Y	- -
- -	X-Y	- -

AUXILIARY LOSSES AND SOUND LEVEL

MVA	Class	Cooling	Sound Level dB
168.00	ONAN	- -	78
224.00	ONAF	9,200	80
280.00	ONAF	18,500	81

The above va... equipment (heaters, control devices, etc.) losses of 2,000 watts

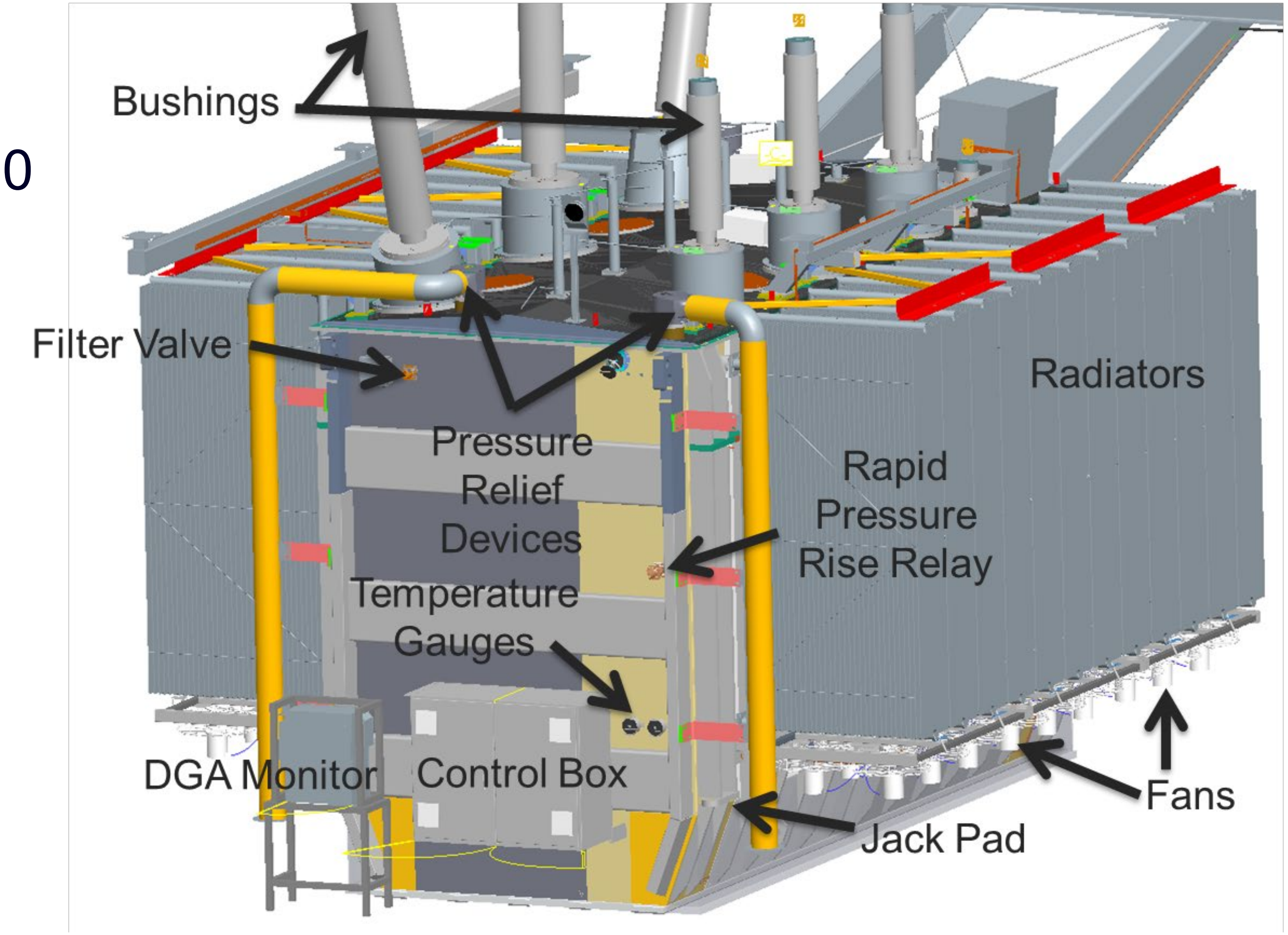
INSULATION LEVELS (KV)

PERFORMANCE BASED ON A LOADING OF

Class	Cooling	Sound Level dB
ONAN	- -	78
ONAF	9,200	80
ONAF	18,500	81

Accessories

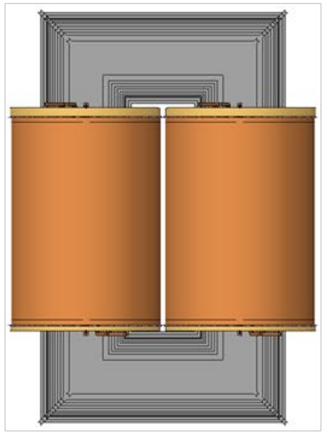
Accessories C57.12.10

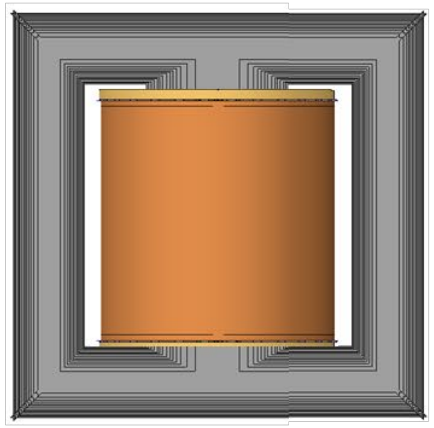


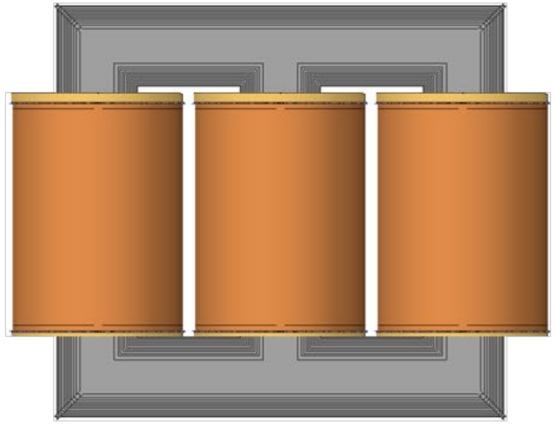
Transformer Internals

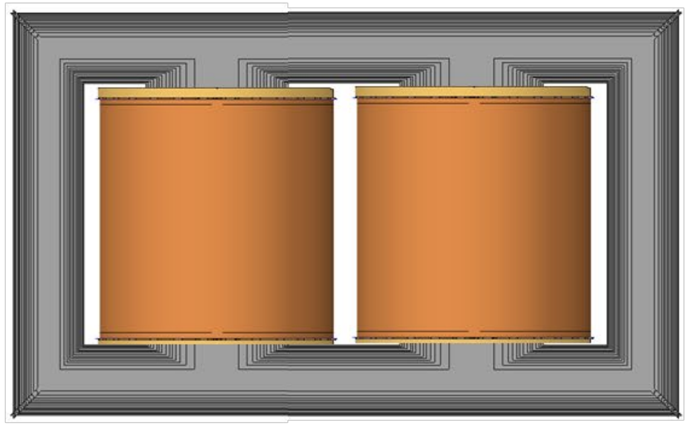
Types of Core & Core Parameters
Types of Windings & Conductors
Insulating Materials

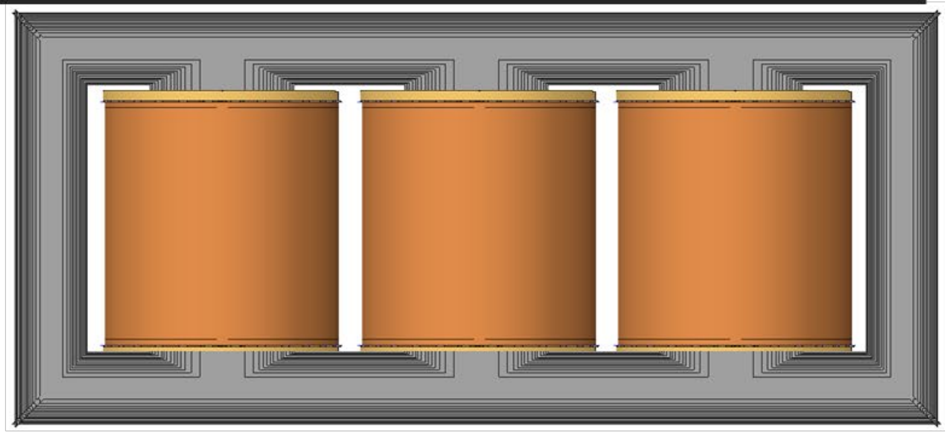
Different types of Core Construction


Single Phase, 2-Limb Core form


Single Phase, 3-Limb Core form


Three Phase, 3-Limb Core form

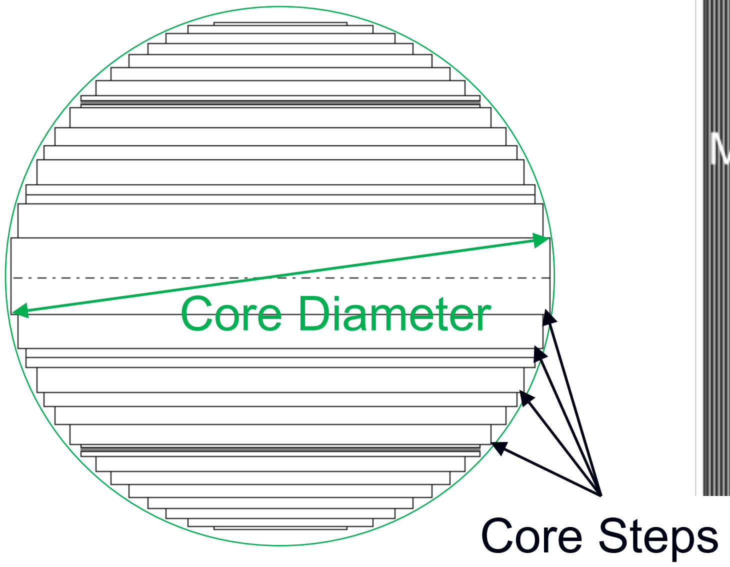

Single Phase, 4-Limb Core form

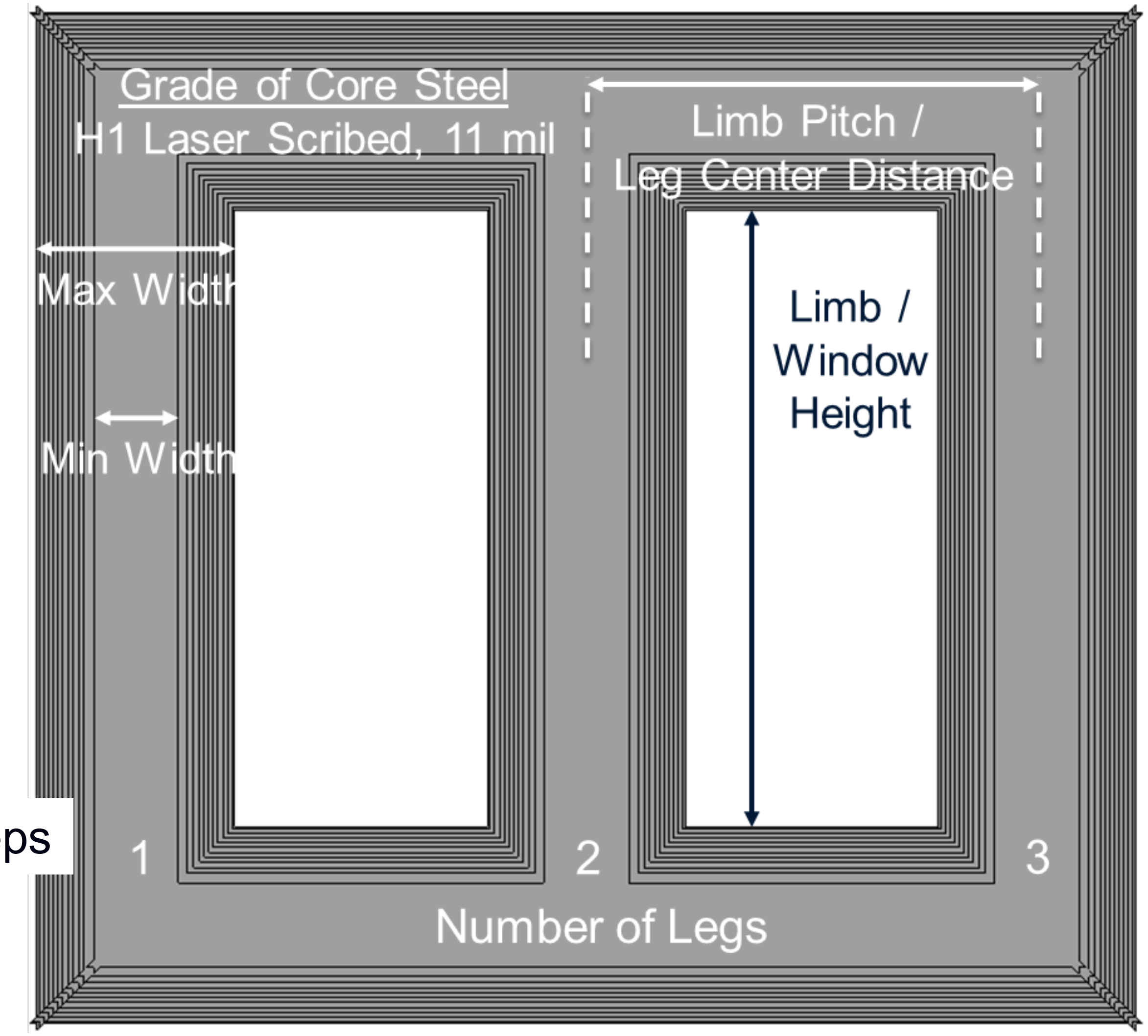

Three Phase, 5-Limb Core Form

Core Parameters

Core Considerations:

- Flux Density
- No Load Loss
- Sound
- Excitation Current
- Temperature Rise
- Internal
- Outer Packet
- Tie Plate
- Clamps
- Tie Plate
- Lifting + Clamping Stress
- Short Circuit Stress





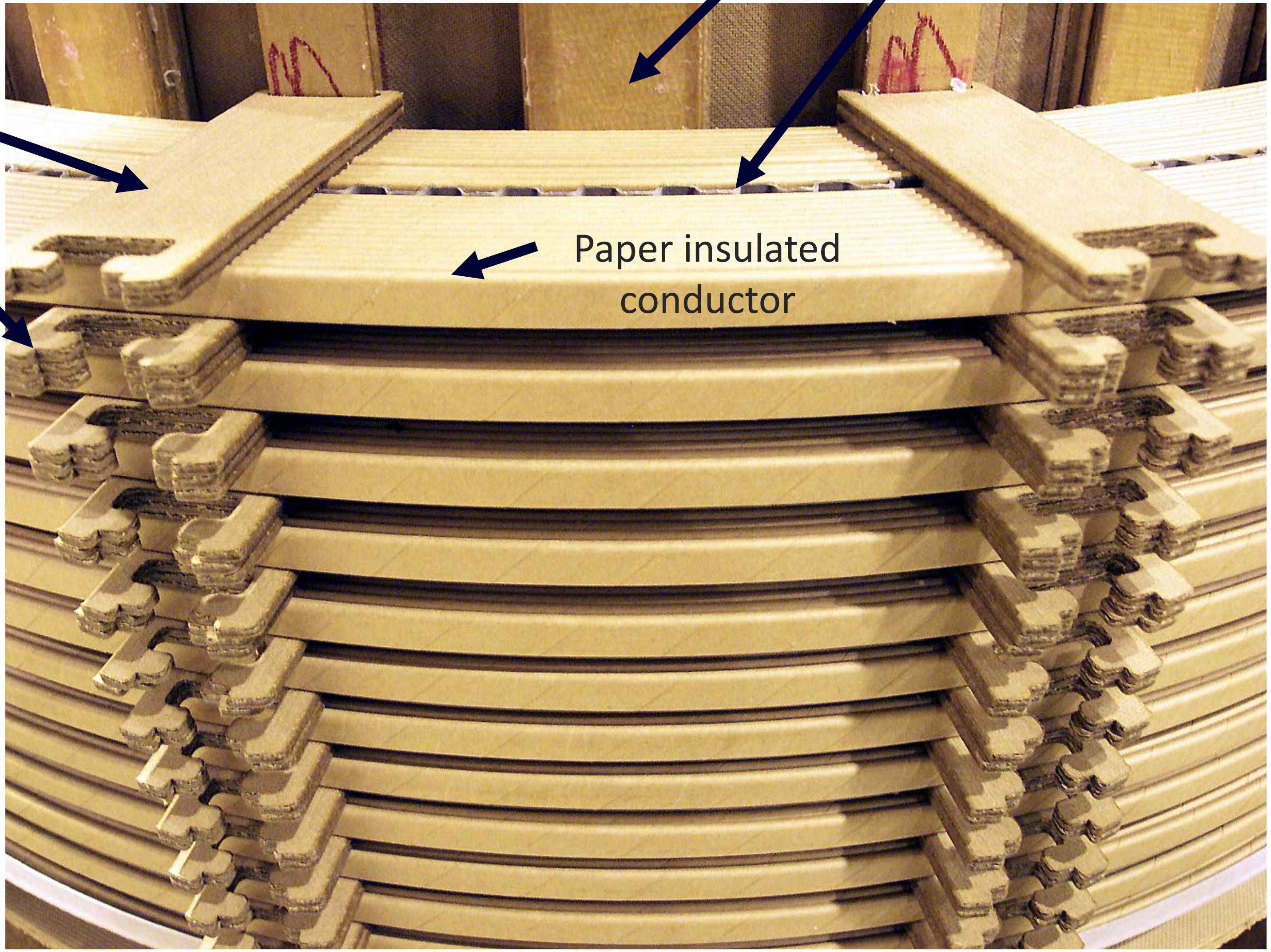
Types of Windings

Winding Types

- Screw (Helical)
  - LV, Series (Booster) transformer
- Continuous Disc
  - HV, LV, Series (Booster)
- Layer/Barrel
  - Regulating (RV) and Tertiary windings (TV)

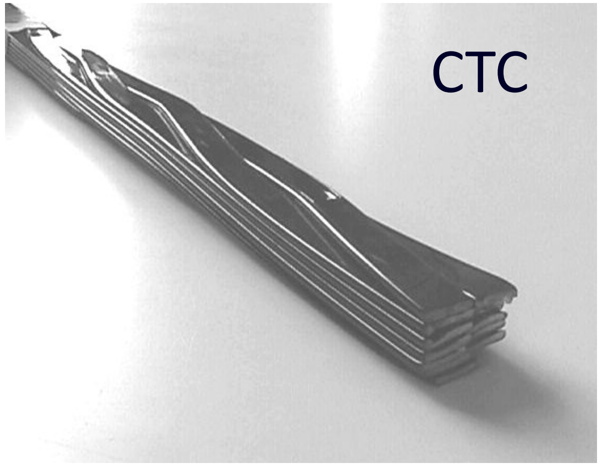
Above winding types may use magnet wire or CTC

Close up of Coil Construction (disc/screw)

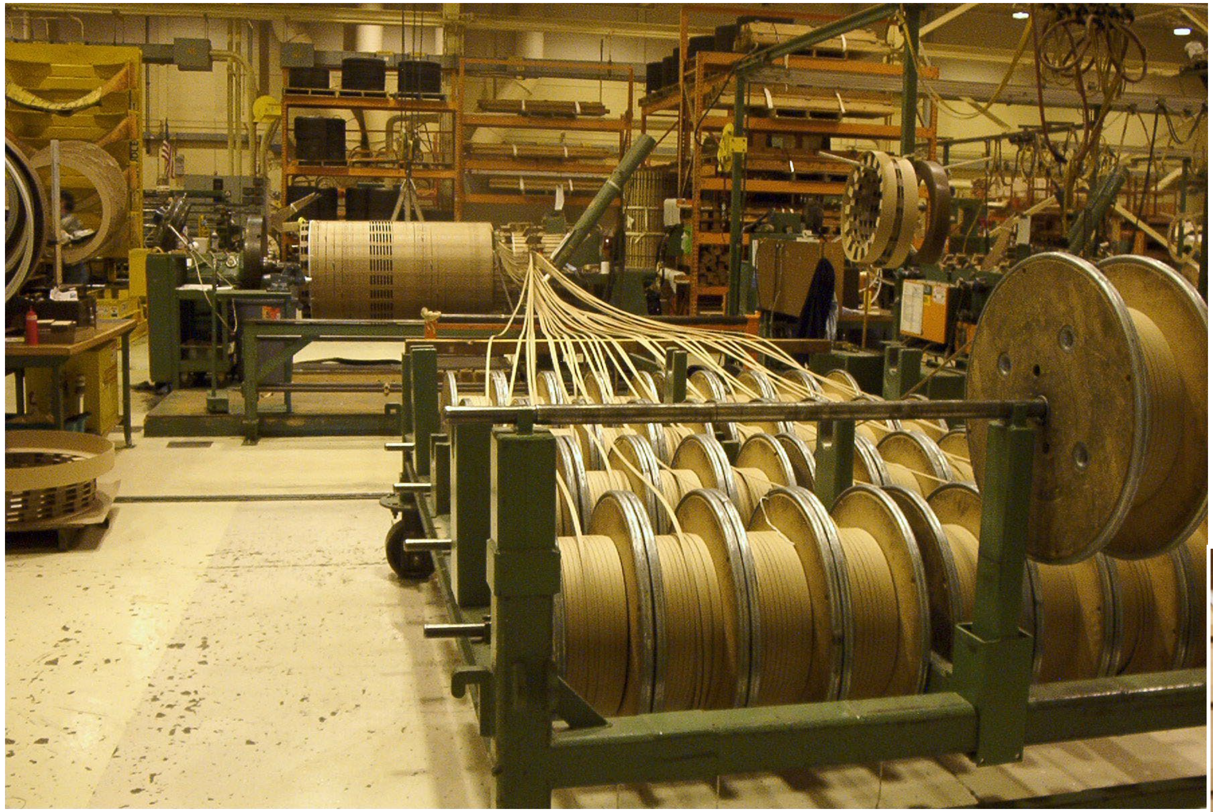


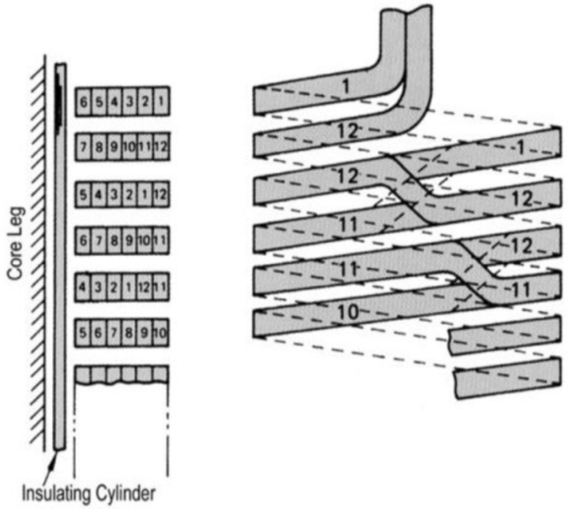
Type of conductors

- Copper Strip or Foil
- Bus bar
- Rectangular wire (MW)
- Continuously Transposed Cable (CTC)

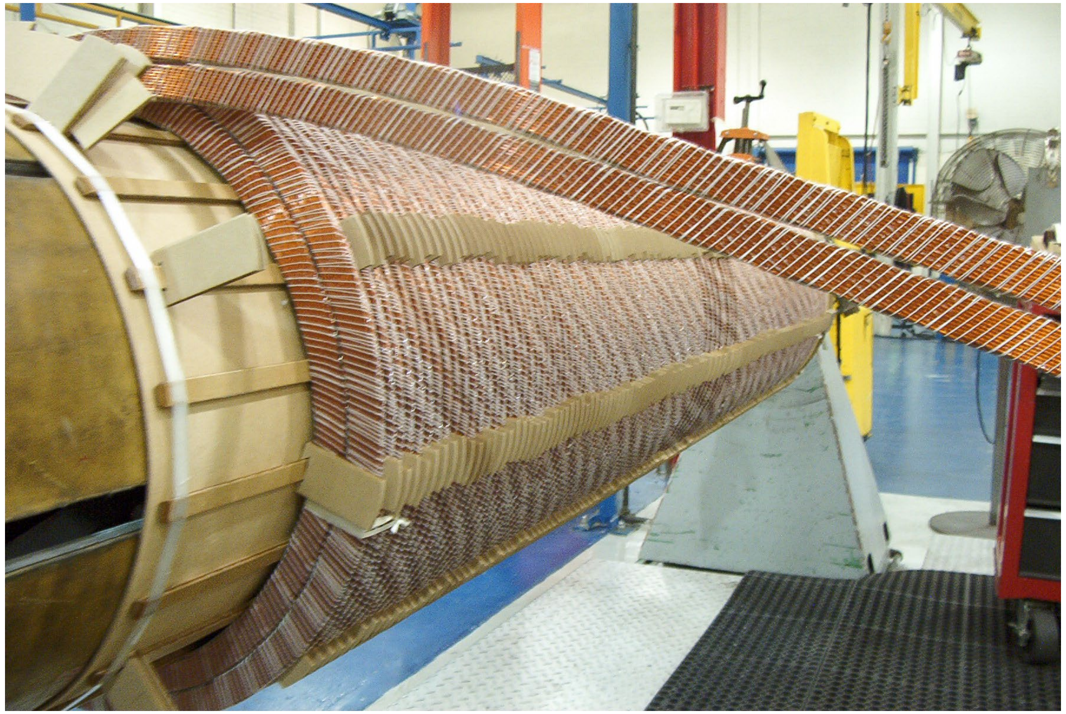


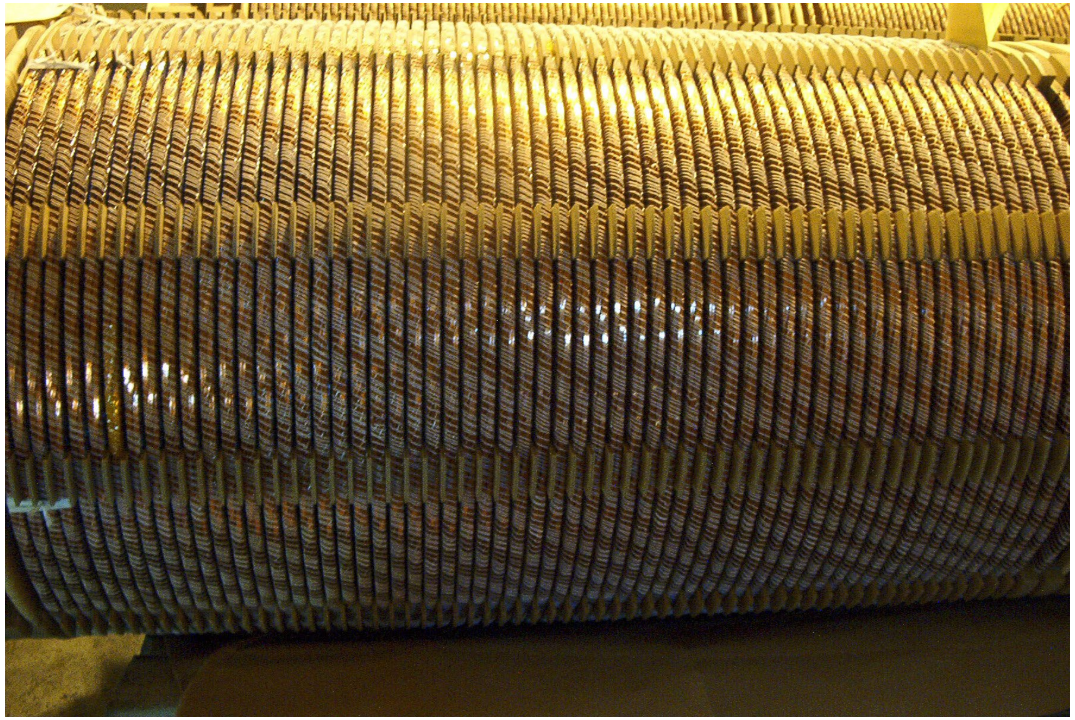
Helical / Screw (1 x 30 strands per turn)



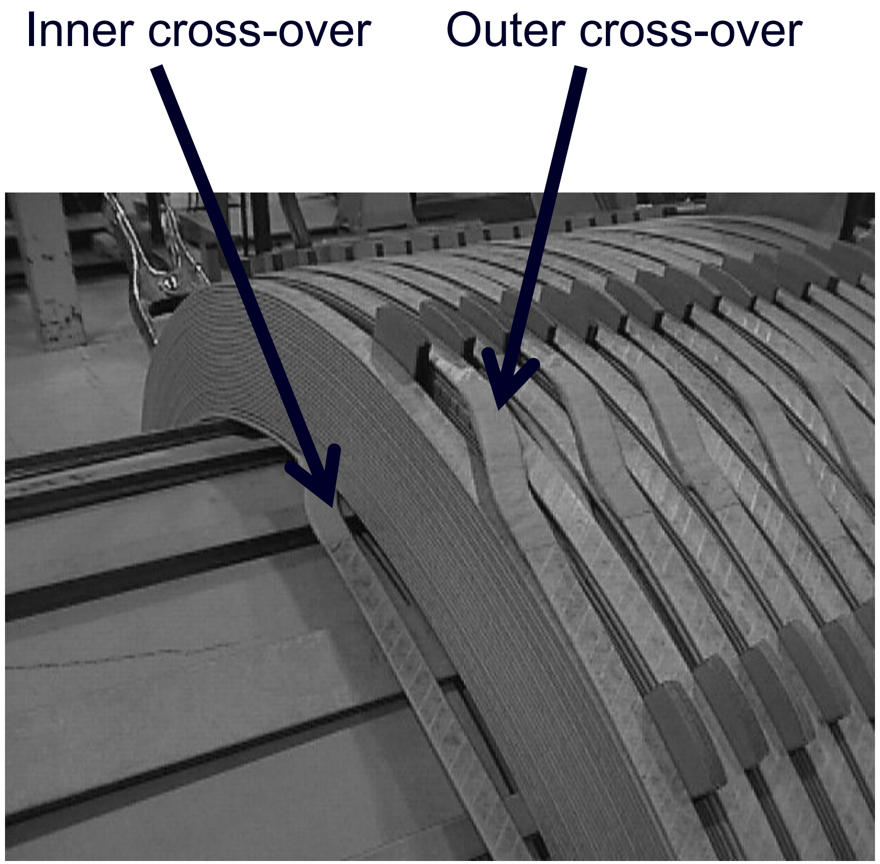


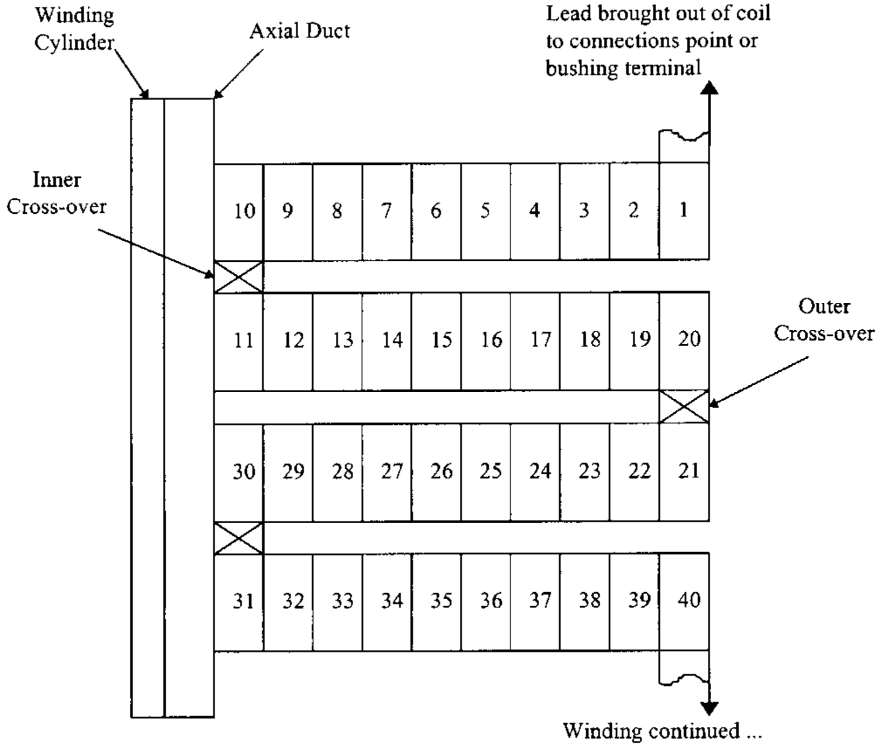
Helical Winding with two CTCs





Continuous Disc Winding (1 strand per turn)

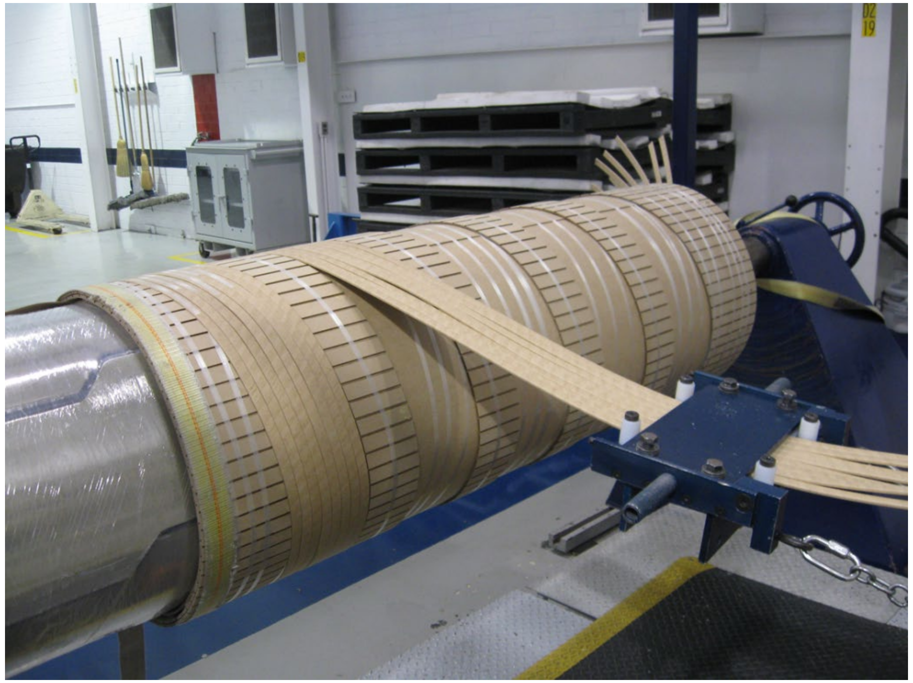




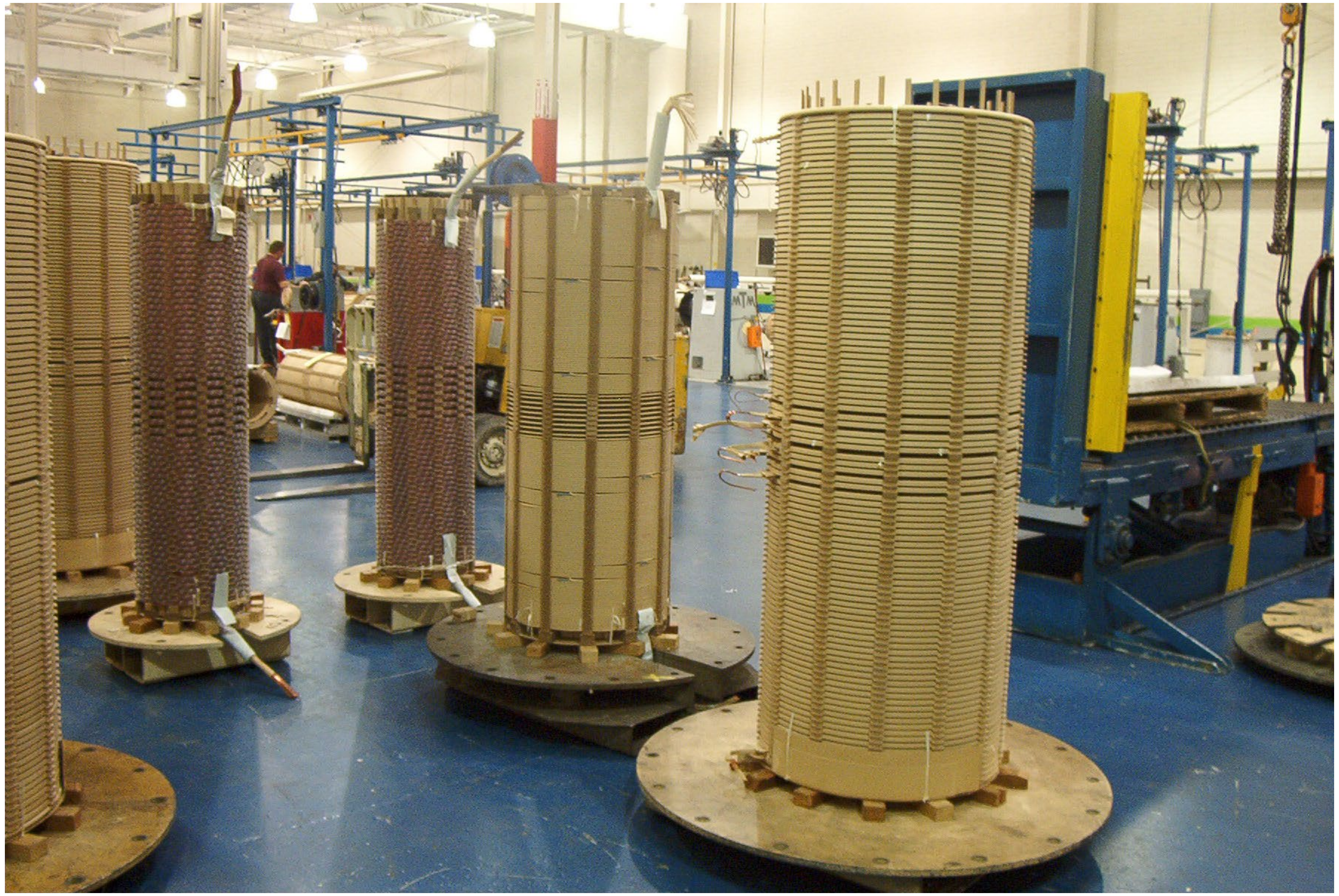
Disc Winding with Magnet Wires

Layer Type Winding

SLL / Layer / Barrel



Full Set of Windings



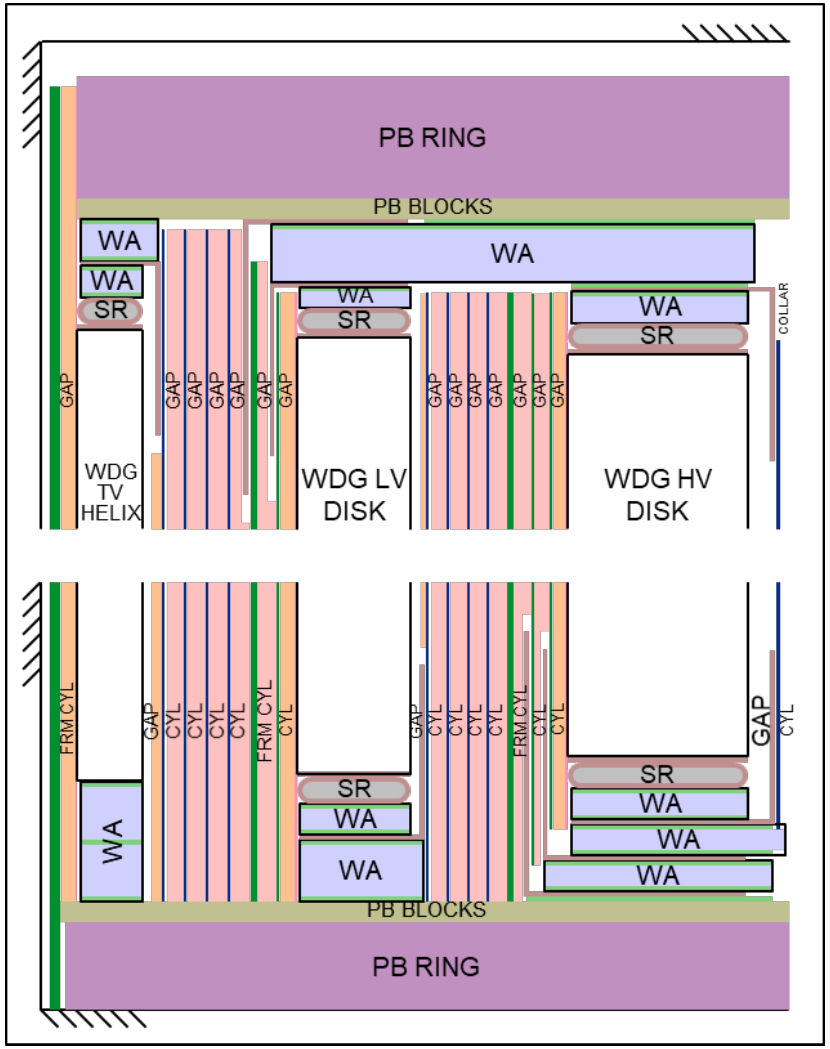
Insulation Materials

Major Insulation

Insulation of windings to ground, core, other windings within the phase and to other phases

Materials

- Pressboard (cellulose)
  - High density (TIV) – cylinders
  - Medium density (Hi-Val) – collars
  - Layered TIV (TX2) – rings, washers
- Nomex – for higher temperatures
- Laminated Wood – rings
- Kraft Paper (cellulose) – leads
- Copaco (cotton based paper) – leads
- Resin/epoxy materials – on metal parts



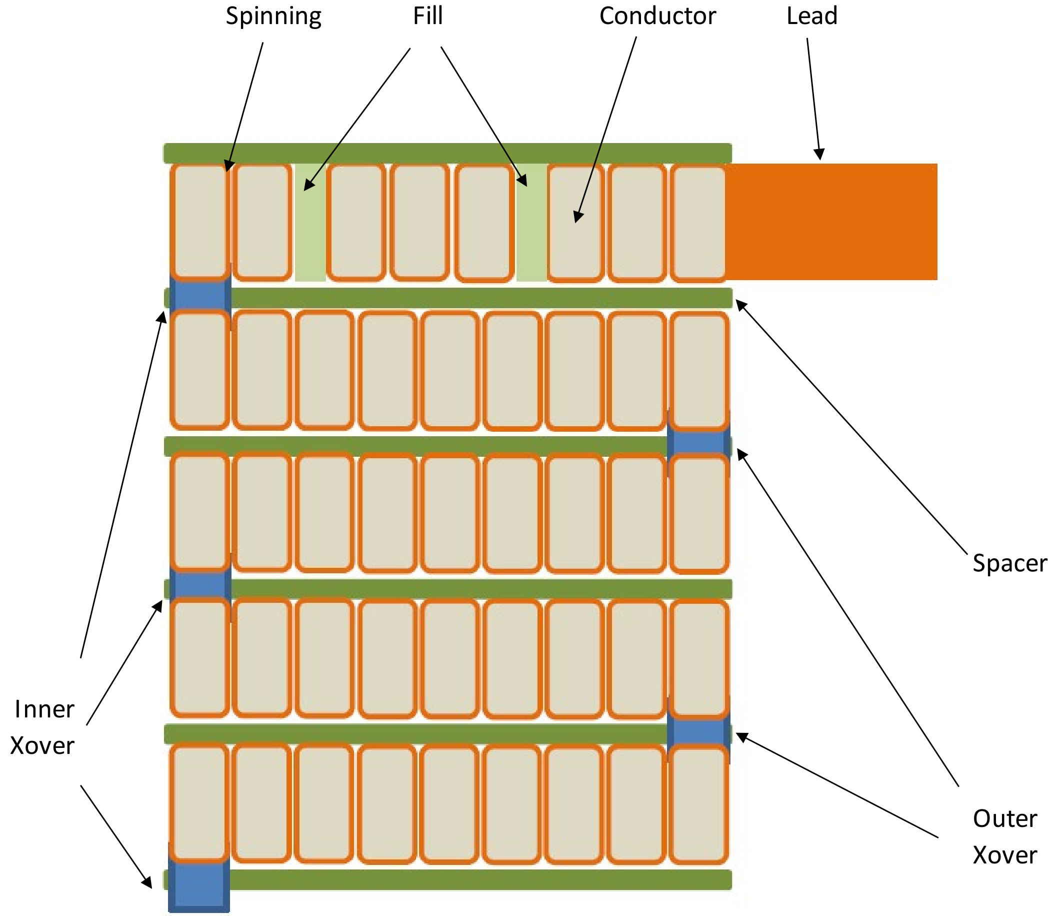
Insulation Materials

Minor Insulation

Insulation between different parts of one winding – between turns, strands of conductors, discs or layers

Materials

- Kraft Paper – conductor insulation/spinning
- Nomex – spinning, spacers
- Formvar – conductor insulation
- Epoxy (CTC) – conductor insulation
- Copaco (cotton based paper) – leads
- Pressboard
  - High density (TIV) – spacers
  - Medium density (Hi-Val) – collars, etc.
  - Layered TIV (TX2) – structural parts



Insulation Materials

Insulating Fluids

- Mineral Oil
- Natural Ester

Advantages of Natural Ester

- Slows aging of cellulose
  (equiv. to roughly 10 ˚C lower winding rise)
- Higher Flashpoint (330˚C vs 140˚C)
- Environmental advantage/containment

Drawbacks

- Cost
- Higher viscosity
- Solidifies below -20˚C

Other Materials

Lead Insulation

- Kraft Paper
- Copaco
- Nomex
- Pressboard

Lead Supports

- Maple
- Laminated Wood
- TX2

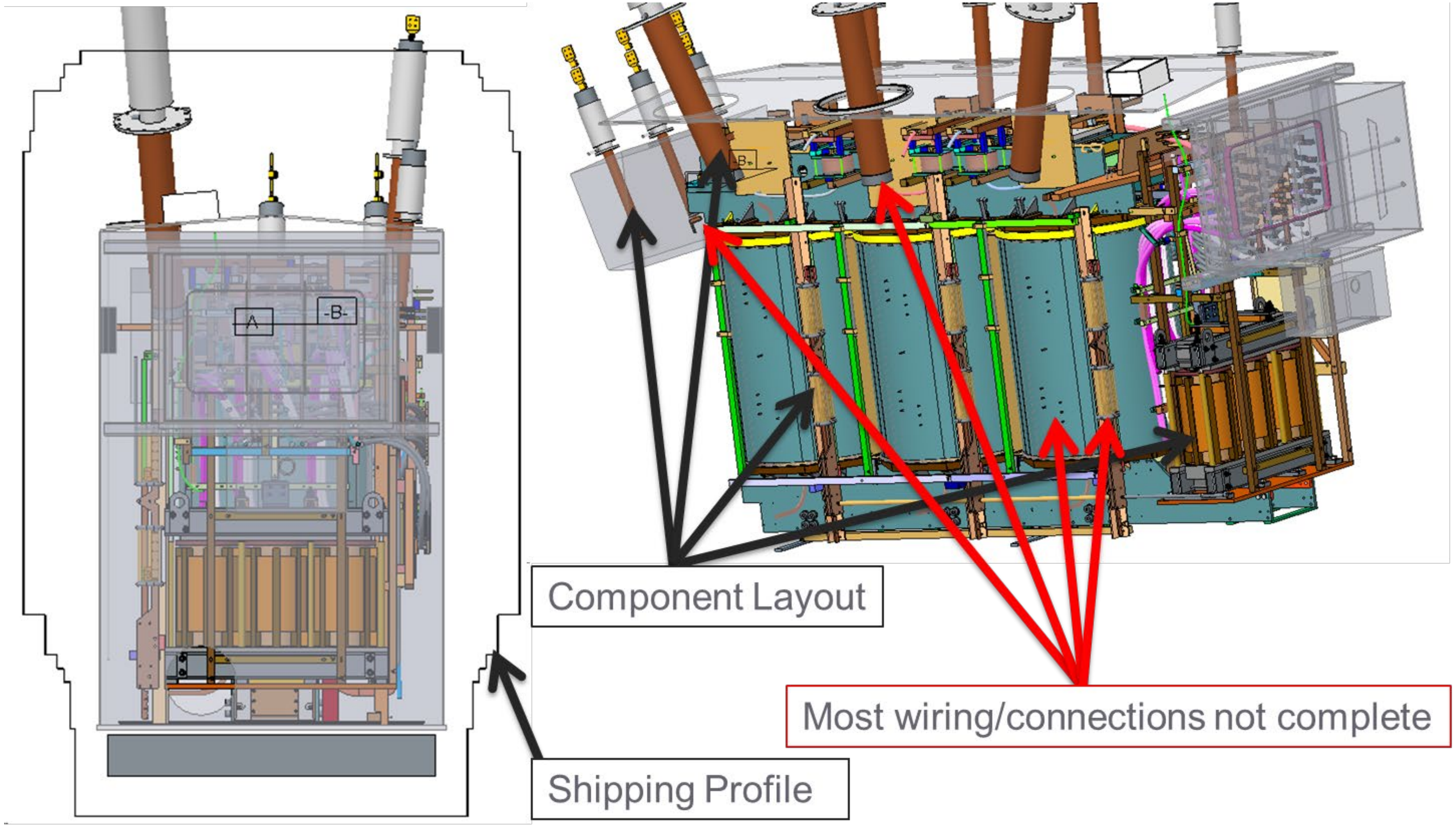
Bushings, Insulators

- Resin/epoxy materials
- Porcelain

Design Process

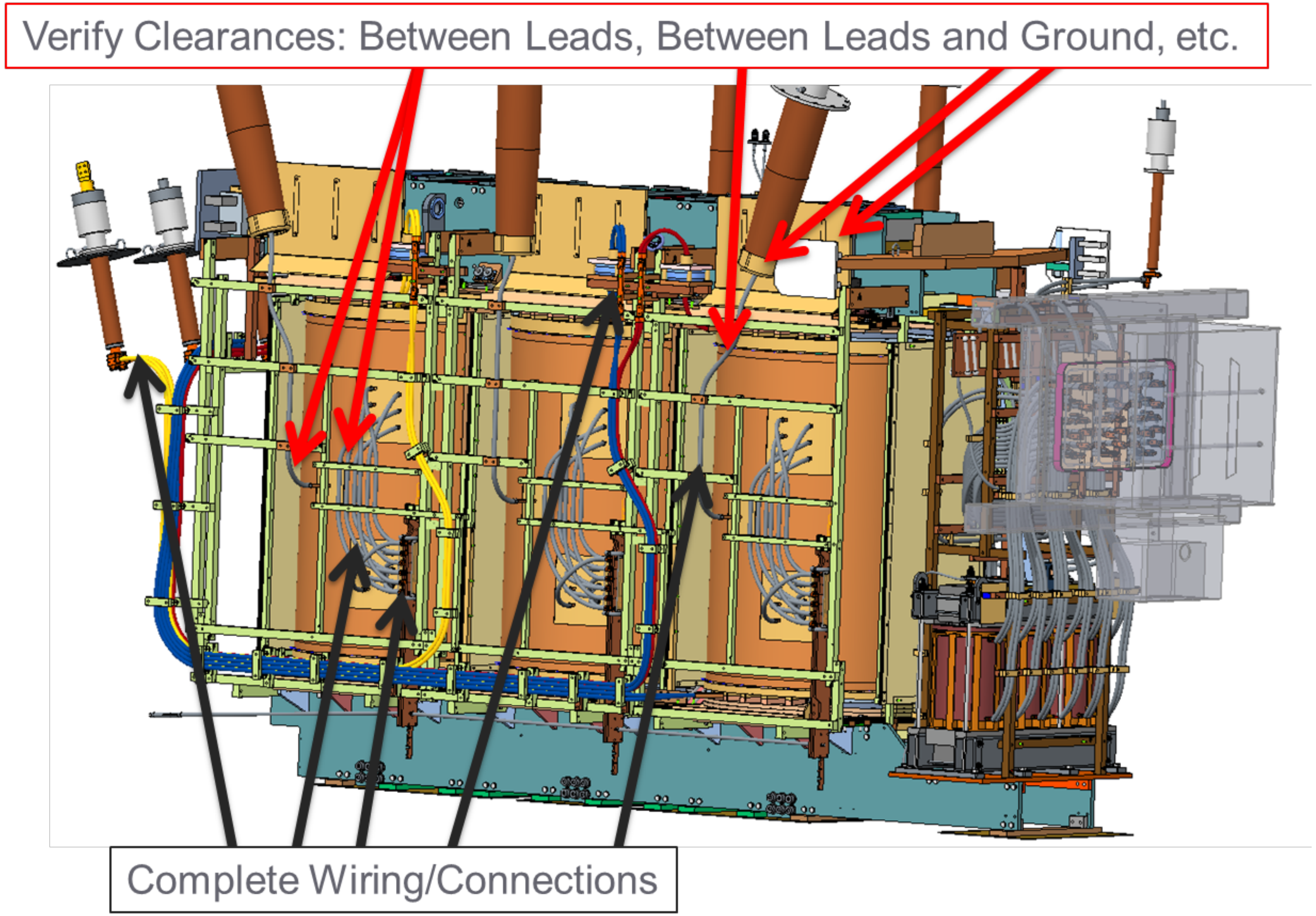
Internal Details

Tank Sizing



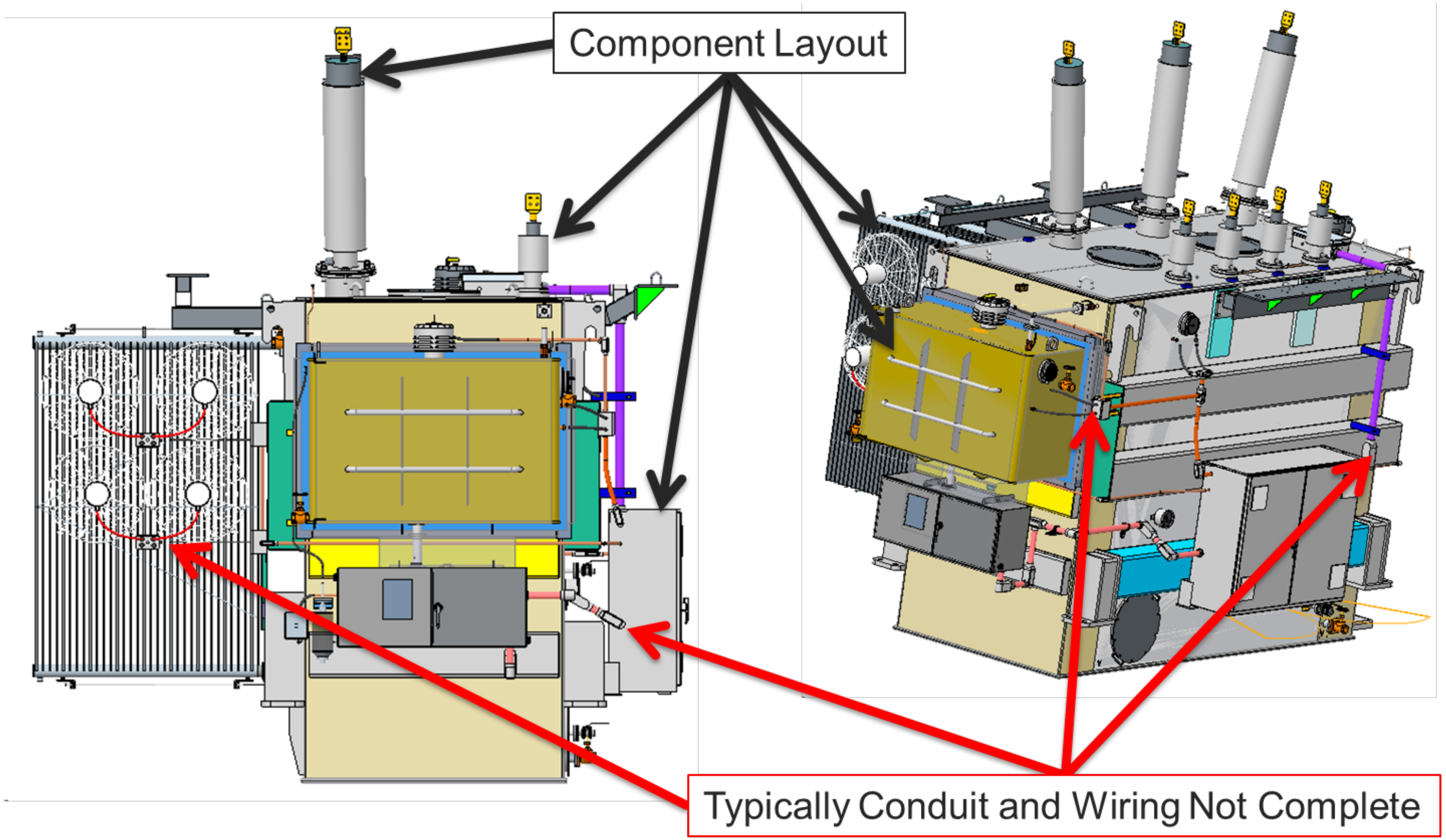
Internal Details

Finalize Design



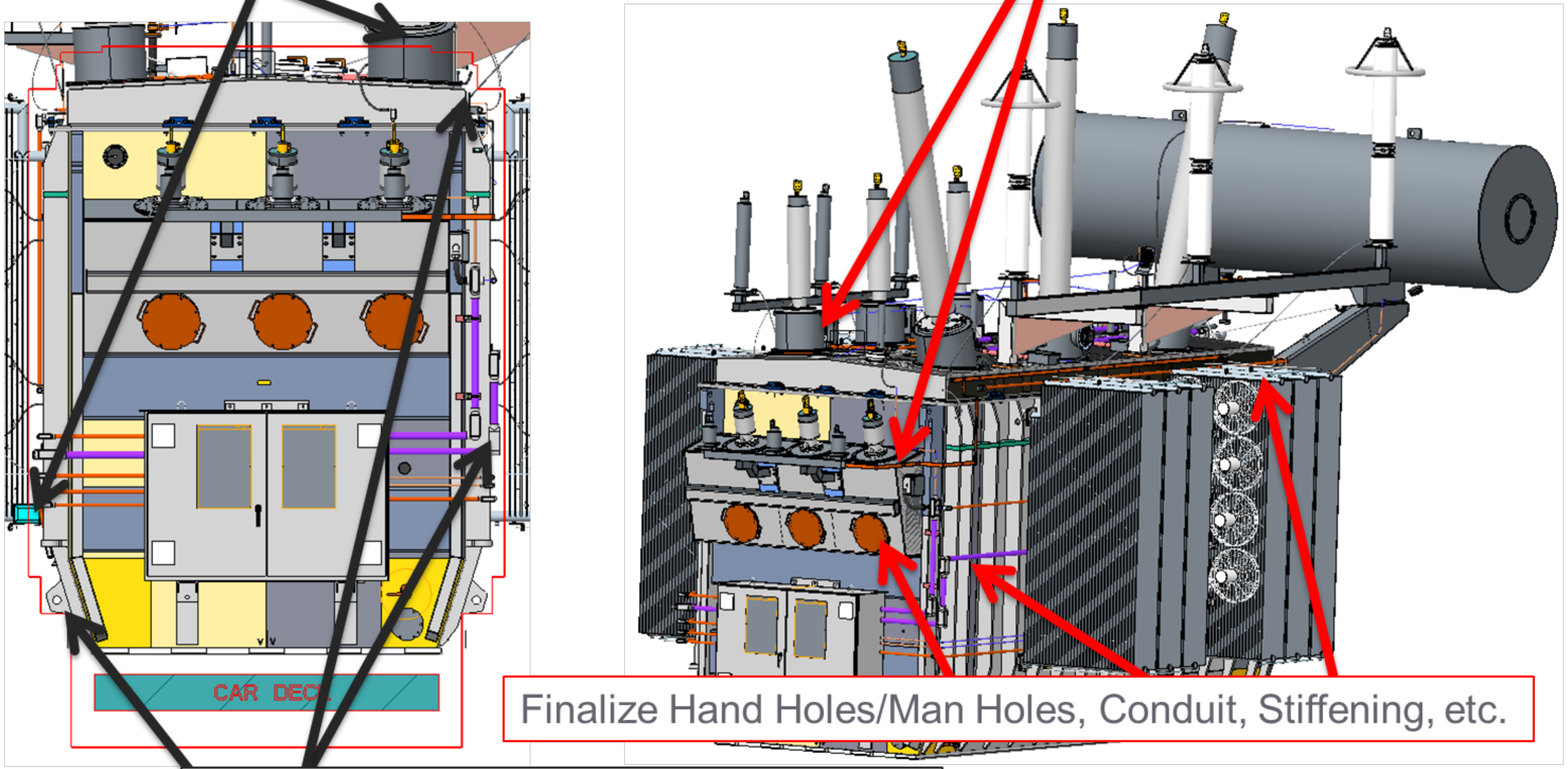
External Details

Model to Generate Outline Drawing



External Details

Finalize Design



Testing

Transformer Tests

Dielectric Tests	Performance Characteristics	Thermal Tests	Other Tests
Transients Lightning Impulse 1. Full Wave 2. Chopped Wave 3. Front of Wave 4. Switching Surge	1. No-Load Losses 2. %Exciting Current 3. Load Losses 4. % Impedance 5. Zero Sequence Impedances 6. Ratio Test • Phase Rotation	1. Winding resistance 2. Heat Run • Oil Rise • Average Winding Rise • Winding Hot Spot Rise 3. Over Load Heat Run 4. Time Constant Heat Run • m&n exponents 5. DGA 6. Thermal Scans	1. Insulation Power Factor (Doble?) 2. Sound Level 3. Megger 4. Core ground 5. Core Loss before & After Impulse 6. Auxiliary Losses 7. Low Voltage Dielectric Test • Controls • CT • Wiring 8. Operational Test 1. LTC 2. Controls 3. Accessories 9. CTs 10. Dew Point 11. 10 kV Single phase excitation (Doble?) 12. Leakage reactance (Doble?) 13. SFRA (Doble?) 14. Framit
Low Frequency (Power) Tests 1. Applied Potential 2. Induced Potential 3. RIV/Partial Discharge			

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Questions

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