Transformers 101

Transformer Regional Technical Seminar

Minneapolis, MN

August 15, 2024

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Dharam Vir
Vice President Engineering

Dharam started with Prolec GE Waukesha in 2004 and is currently responsible for engineering at both the Goldsboro and Waukesha facilities. During his 35+ years in the transformer industry, he has held positions in engineering, testing, production and plant operations. His design experience ranges from development of power transformers up to 765kV, shunt reactors and HVDC transformers. Dharam is an active member of the IEEE Transformers Committee and frequent contributor to industry training programs. He is also a member of the U.S. Technical Advisory Group for IEC Technical Committee 14, Power Transformers, and an individual member of the CIGRE. He holds a BS Degree in Electrical Engineering from University of Delhi (India), an MS in Electrical Engineering from NIT Bhopal, India, and an MBA in Finance and Marketing from Bhopal University, India.

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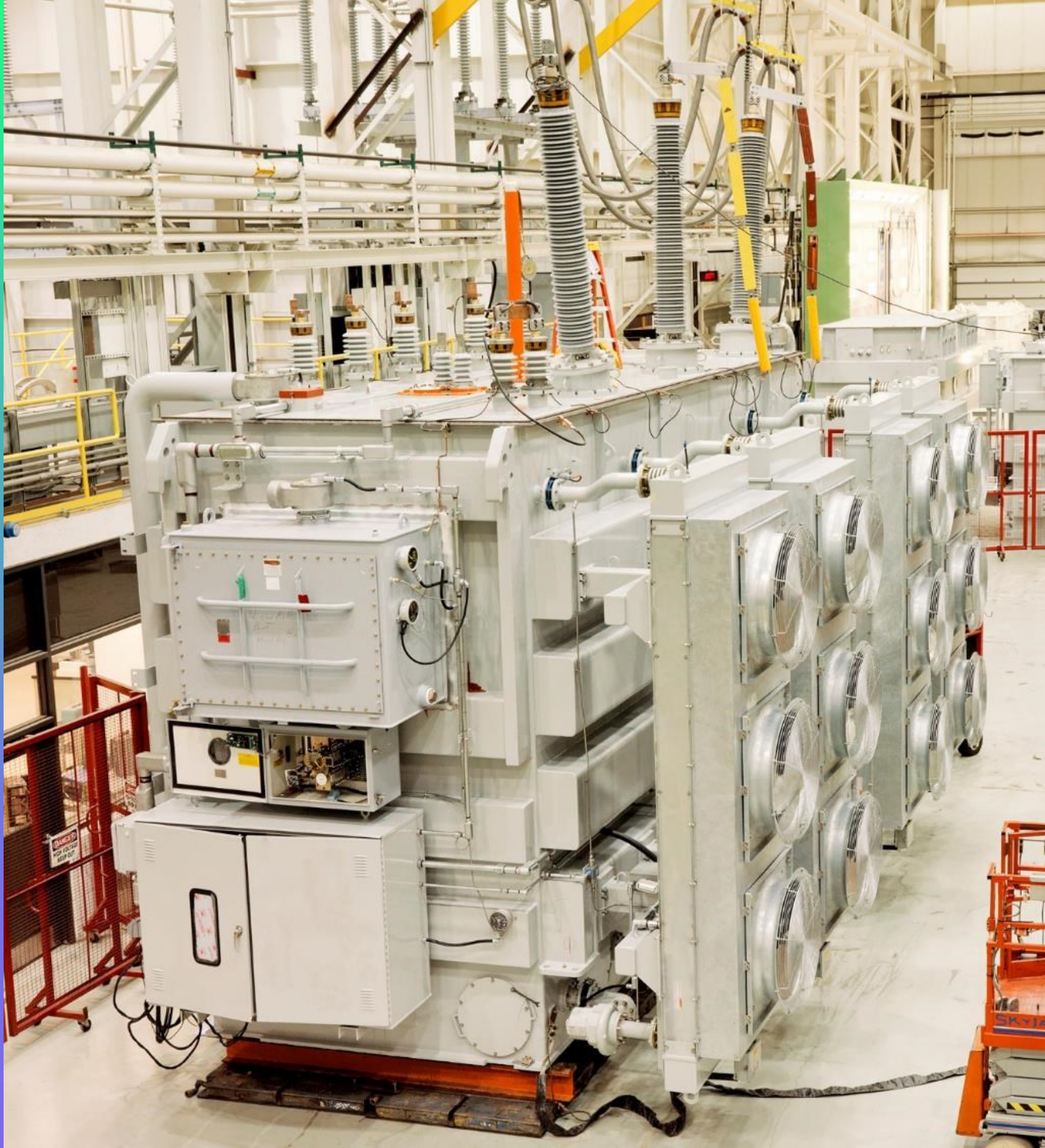

Agenda

- 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.

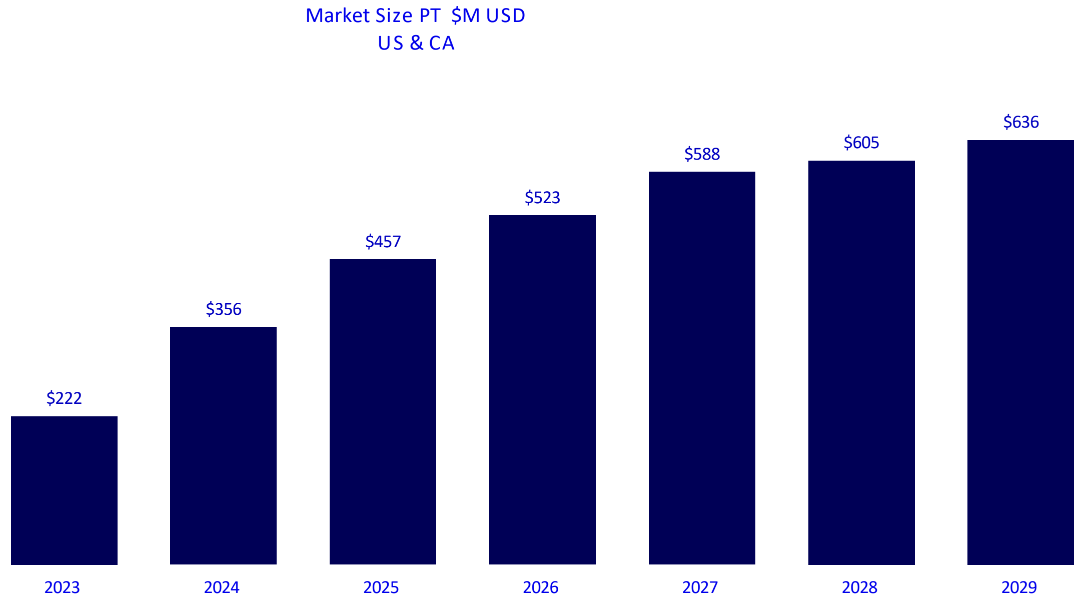
- Renewables growth continues in solar, wind, and battery storage
  - The percentage of renewable generation will jump from 22% in 2022 to 23% in 2023 and 25% in 2024, while nuclear power's share will hold at 19%.
  - Due to inflationary pressures the US offshore wind power capacity under contract dropped 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.

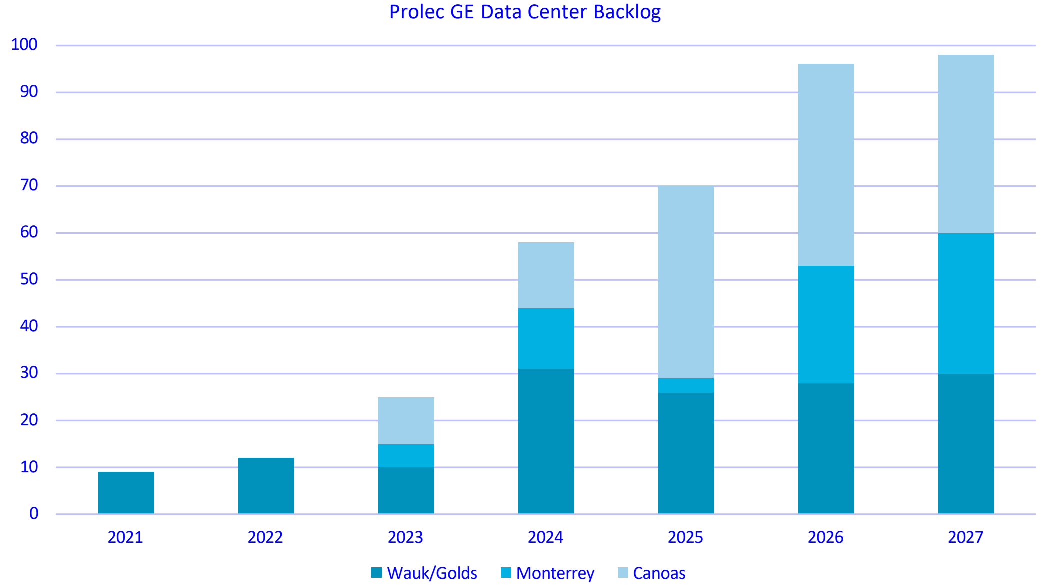
- Data center expansion due to increase in digitalization (AI and Cloud-based storage)
  - US has the largest datacenter market in the world, Electric utilities that serve it point to it a "growth machine".
- Asset aging and replacement
  - Most of the U.S. electric grid was built in the 1960s and 1970s
  - 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

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).

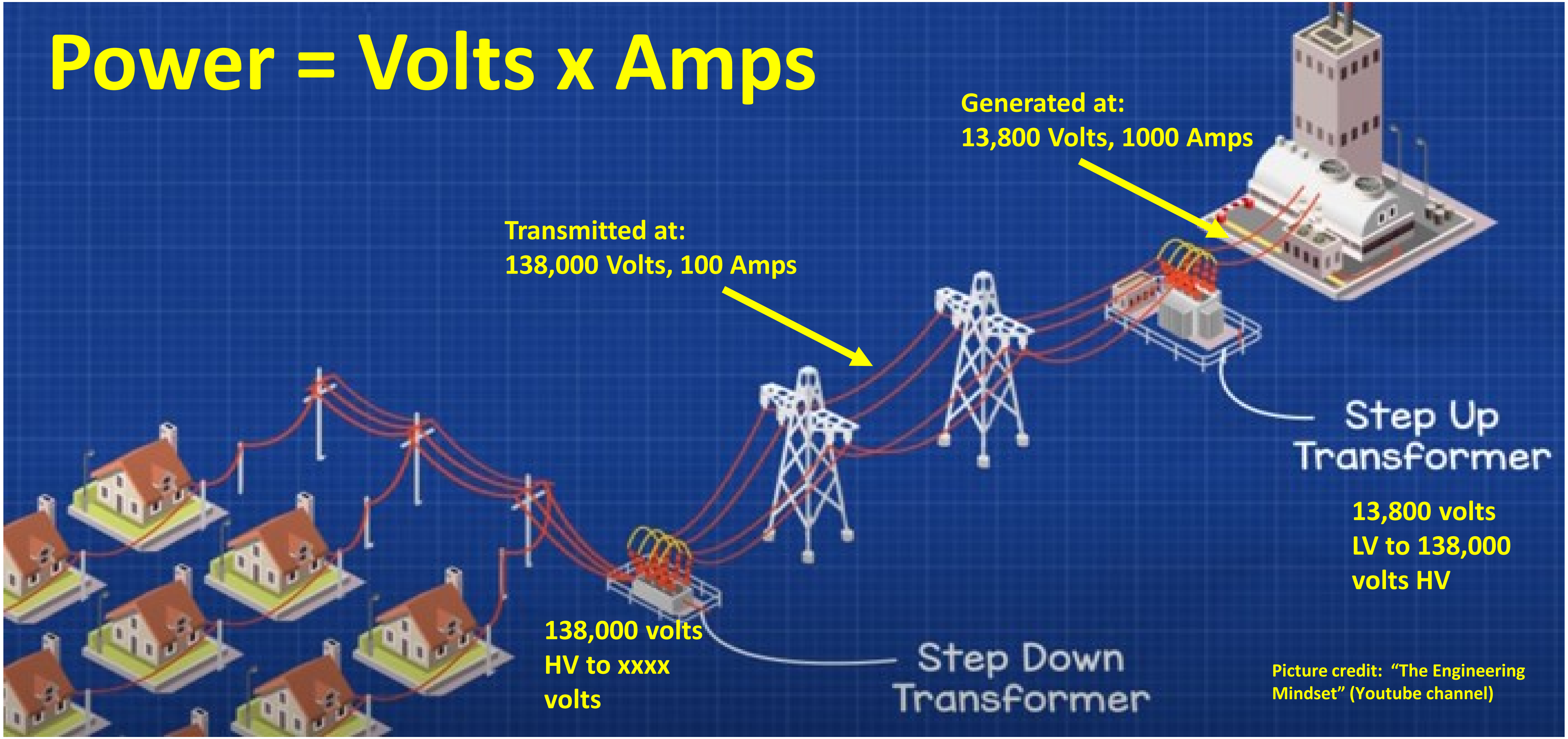
This effect is called "inductance".

Inductance was discovered by Joseph Henry and Michael Faraday in 1831.

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.

Basic Power Transmission



Current & Magnetic Field Relationships

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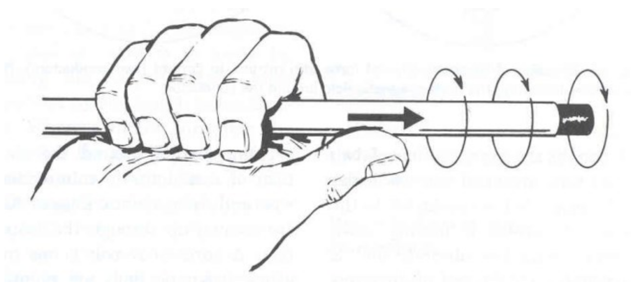
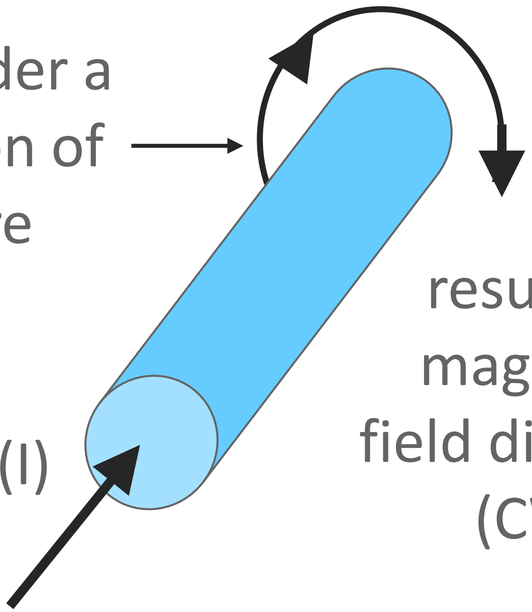
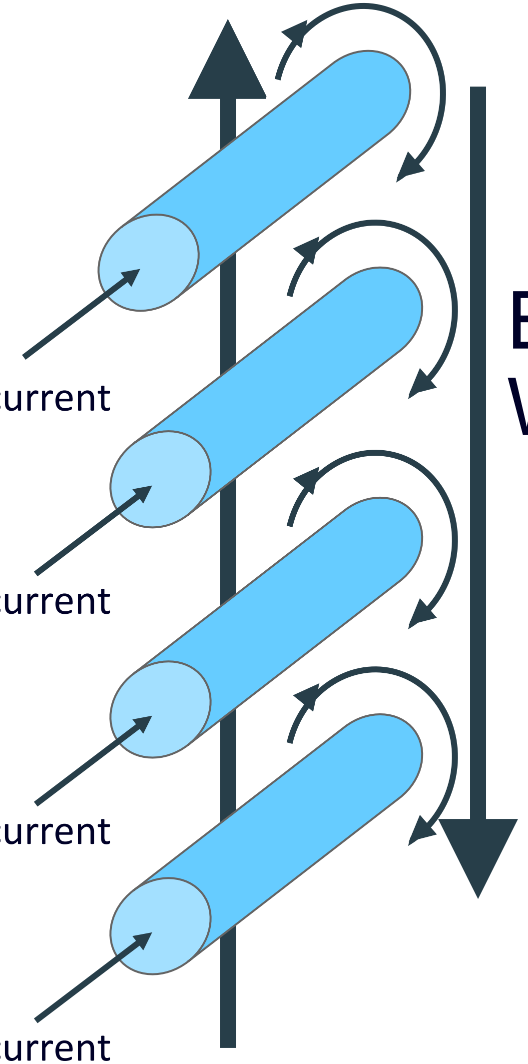


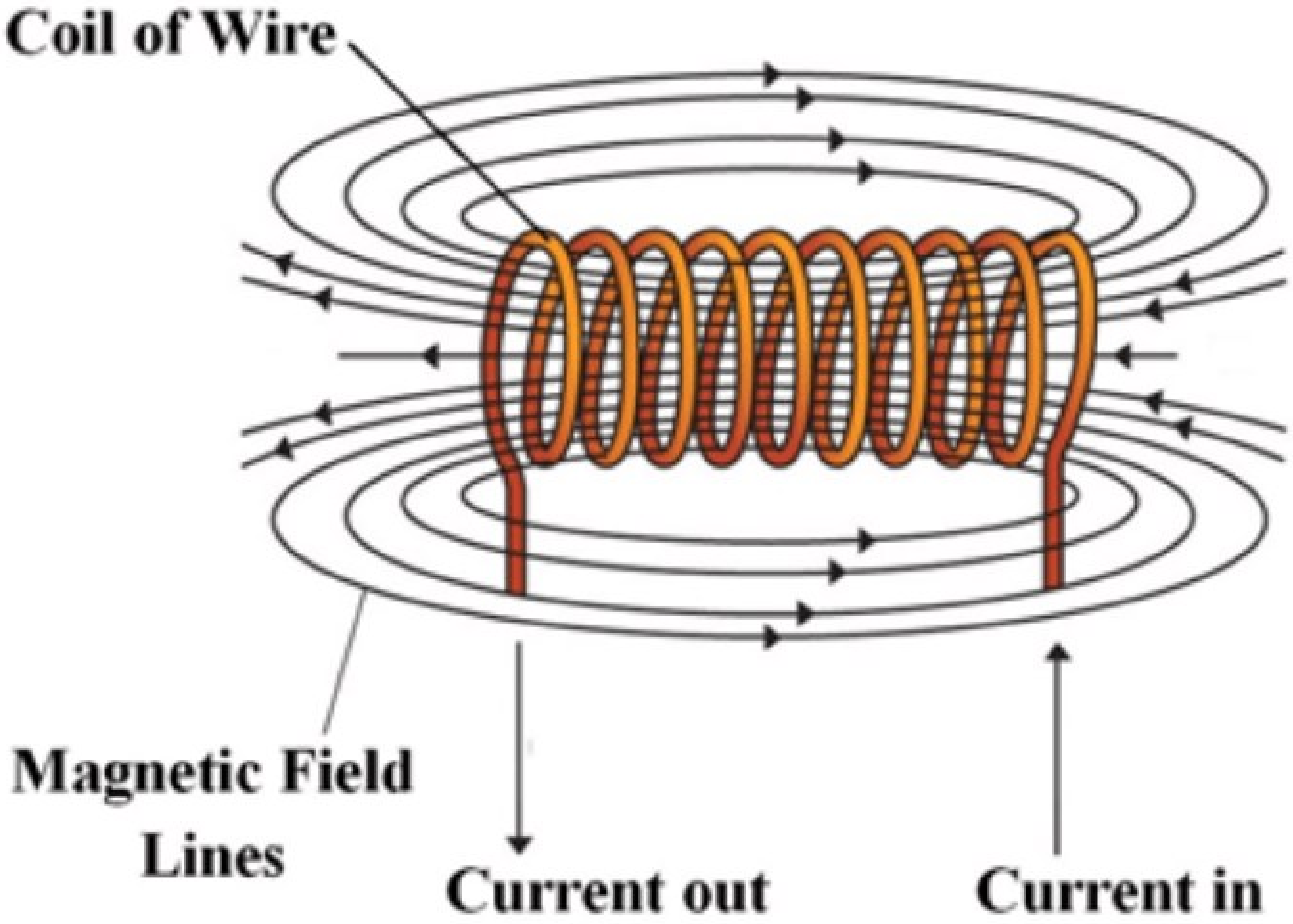
Right hand rule





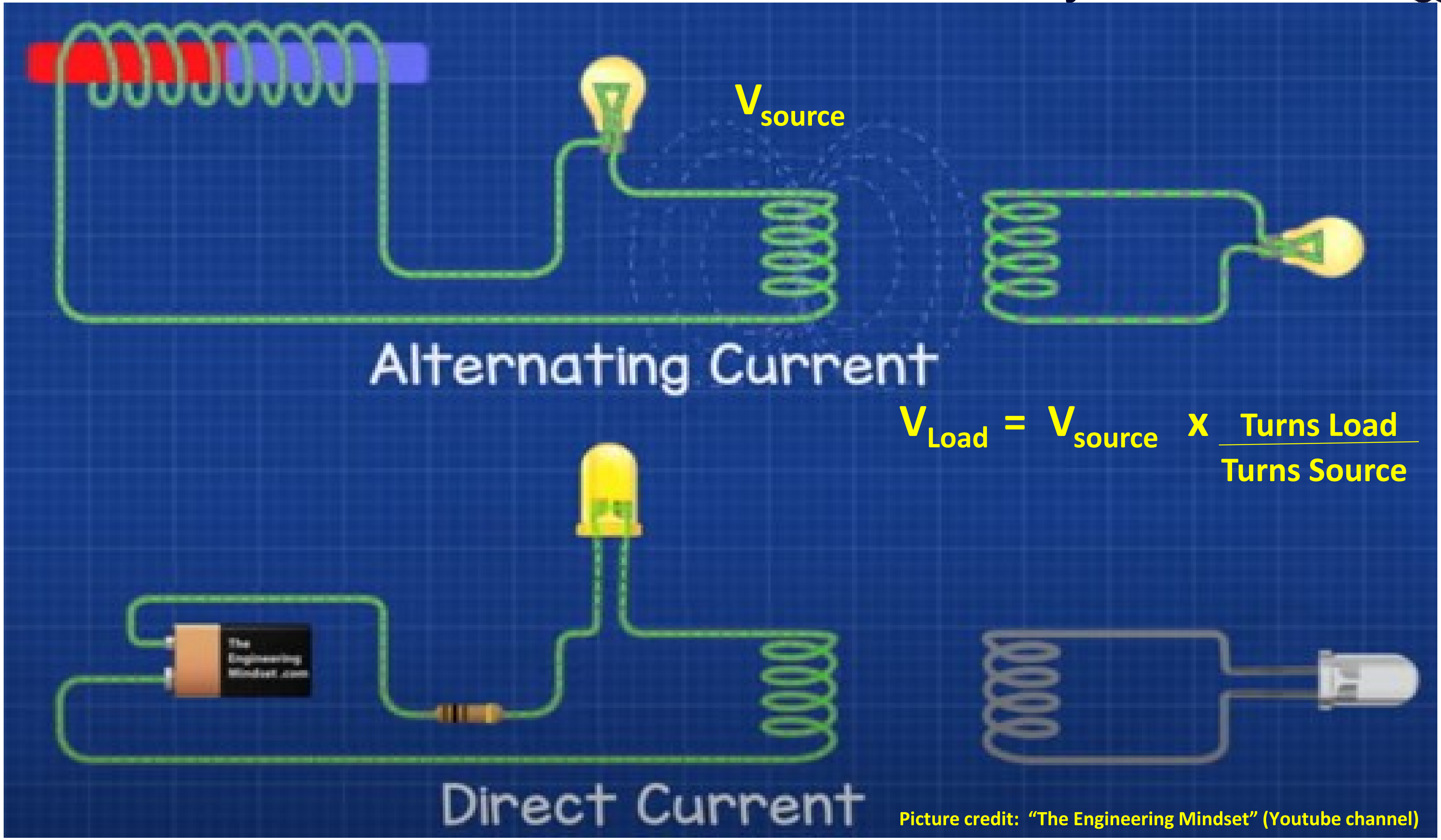
Effect of Many Wires Together

Effect of putting the wire into a coil

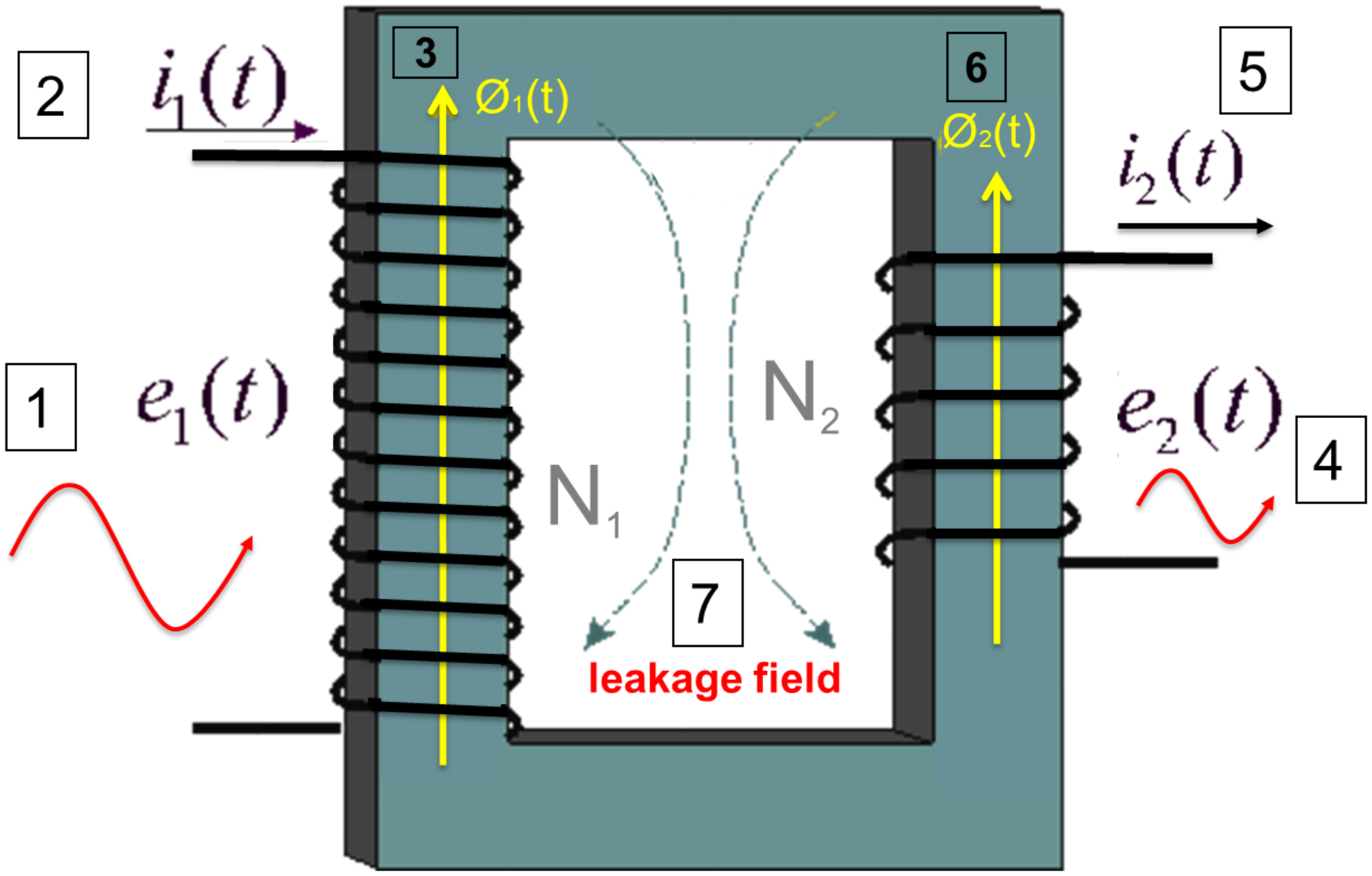


Picture credit:
www.researchgate.net

AC vs DC effects on secondary circuit



Textbook Transformer (step by step)



Vector Diagram –Ideal Transformer

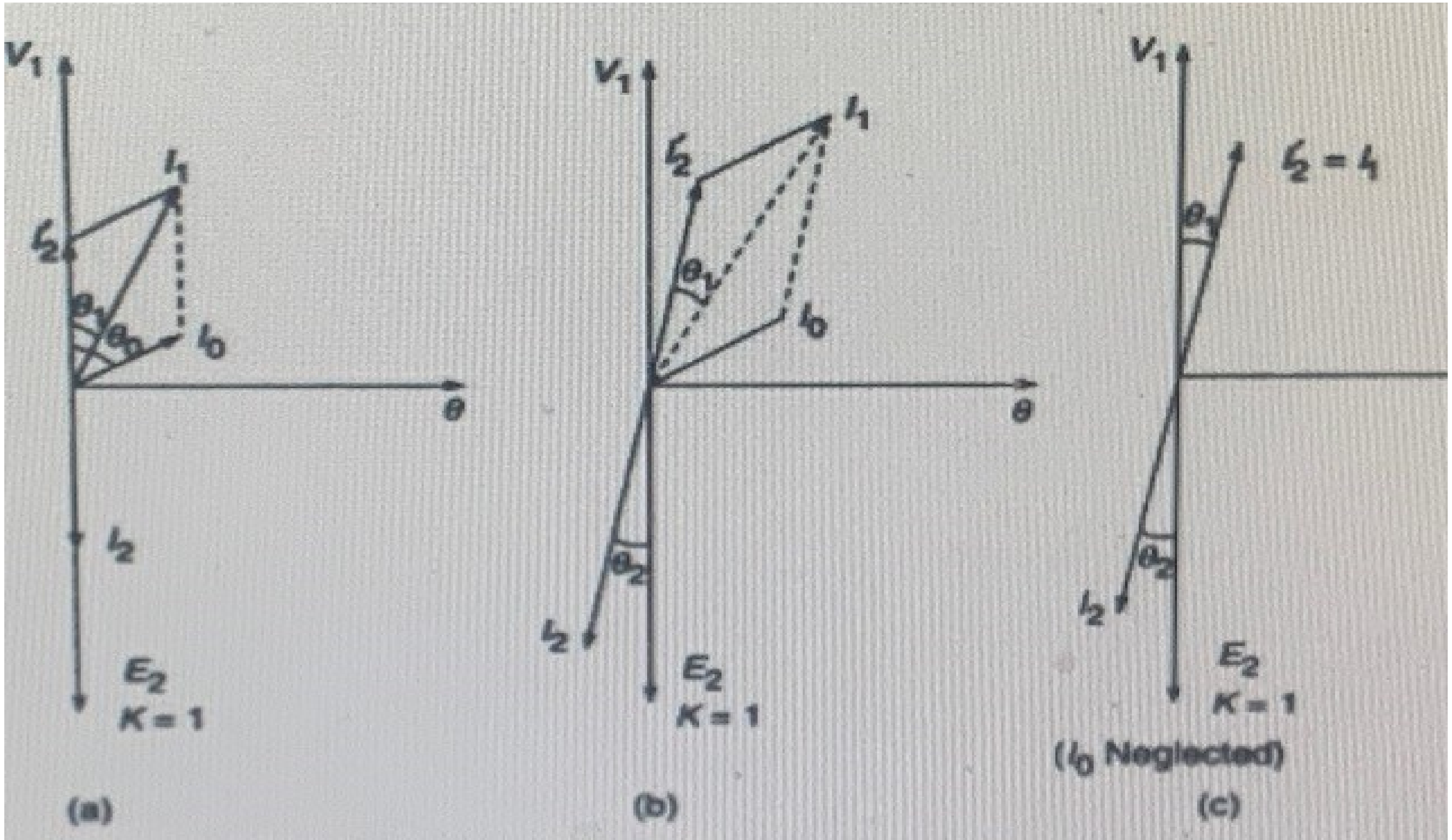
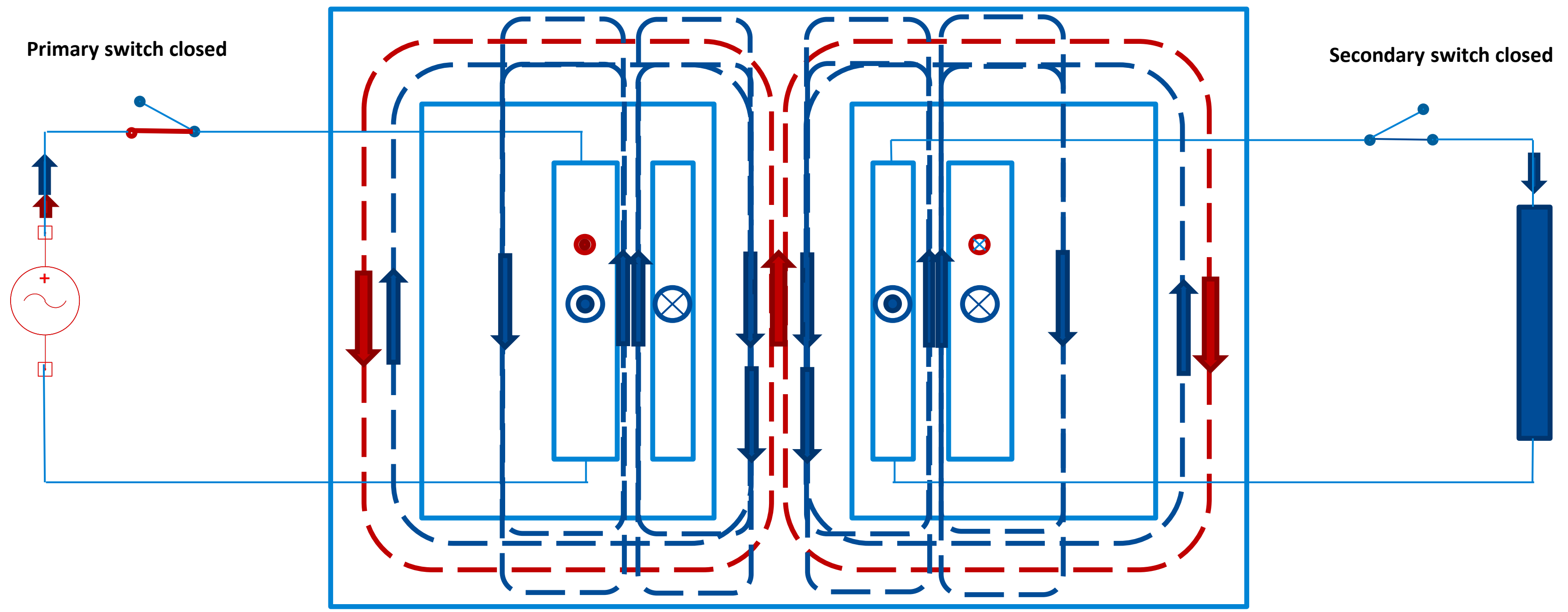
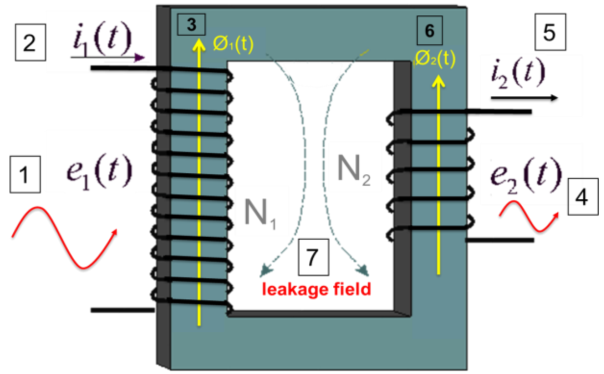


Figure 2.5 *Vector diagram of an ideal transformer.*

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

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

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

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

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

RMS value of counter emf

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

$$E_1 = 4.44 fN_1 \phi m$$

$$E_1 = 4.44 fN_1 Bm\ A$$

For an ideal transformer

$V_1 = E_1$ and $V_2 = E_2$

$$E_2 = 4.44 fN_2 Bm\ A$$

$$\frac{Volts}{Turn} = E_t = 4.44BAf$$

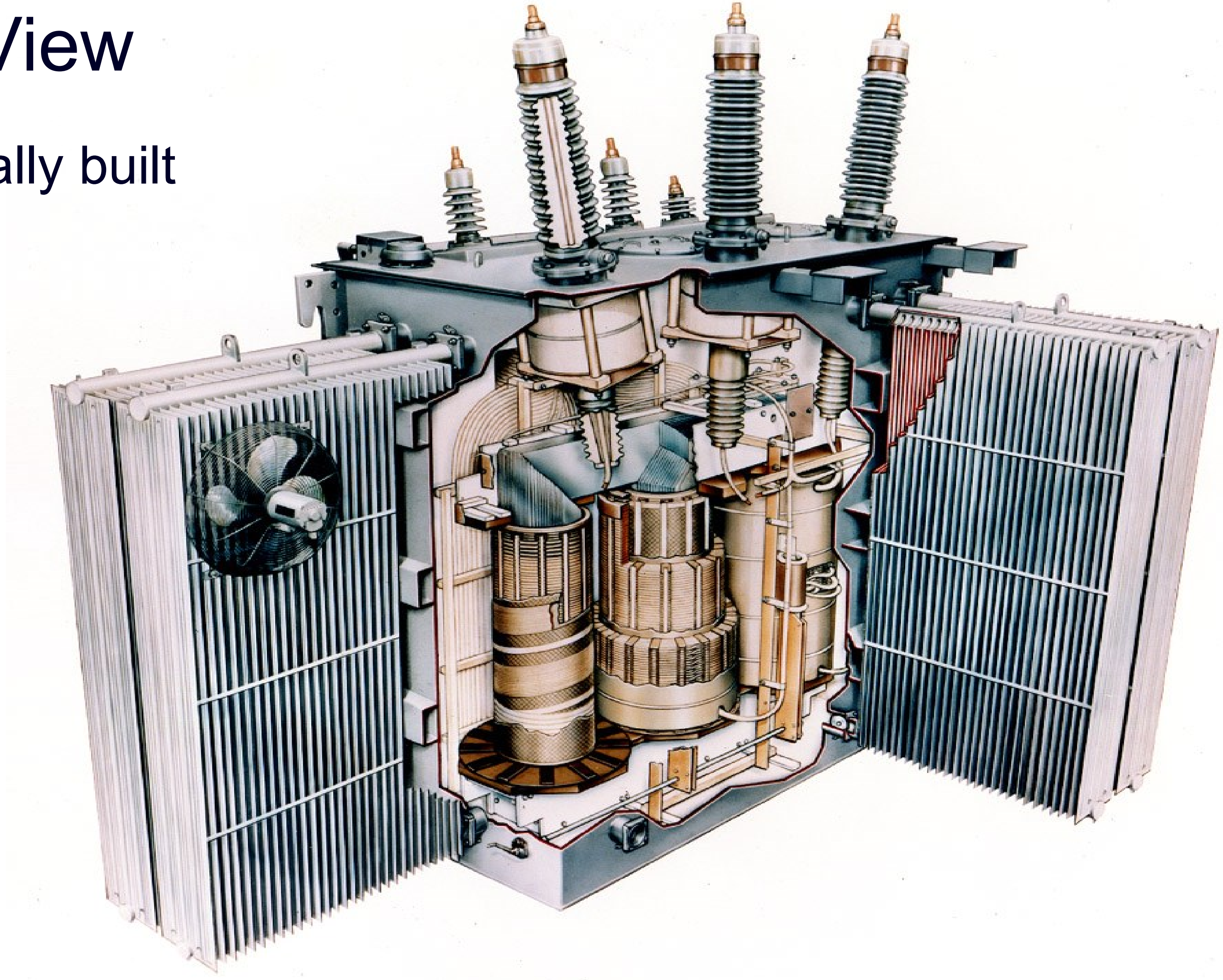
$B = Flux\_Density$

$A = Core\_Area$

$f = Frequency$

Cutaway View

How one is really built



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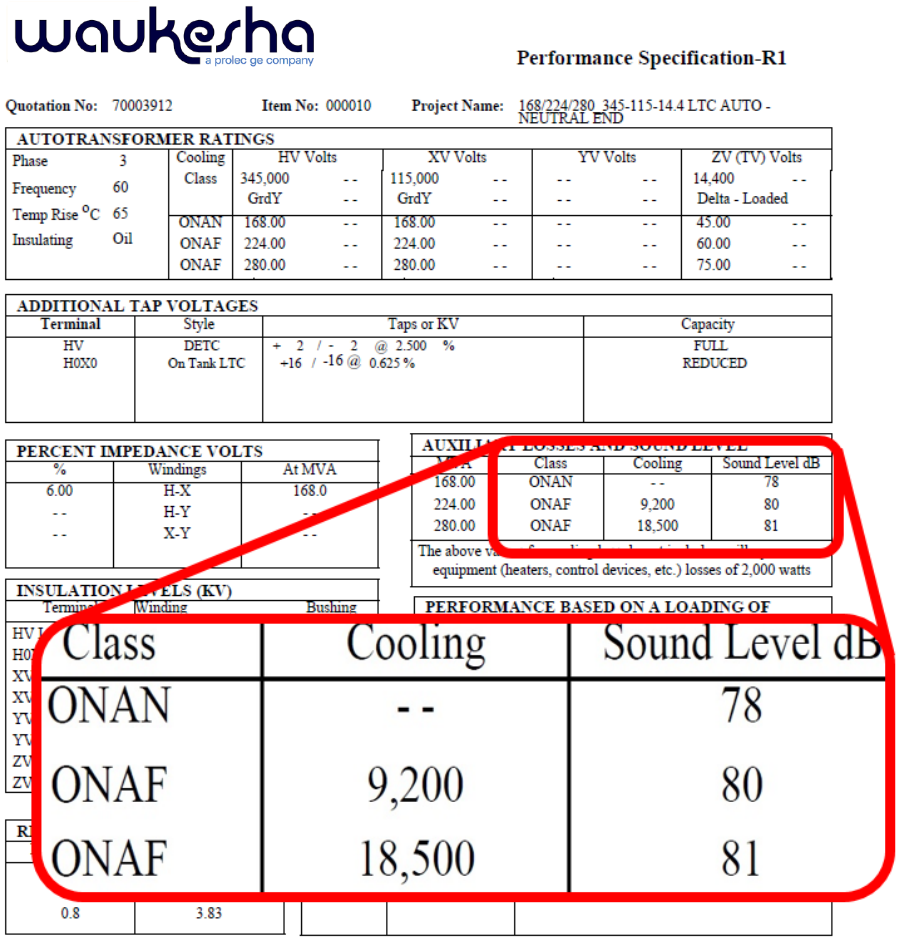
Virtual Factory Tour

Specification requirements and Accessories

Requirements by Specification



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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)

Terminal Winding Bushing

HV ... H0 ... XV ... XV ... YV ... YV ... ZV ... ZV ...

PERFORMANCE BASED ON A LOADING OF

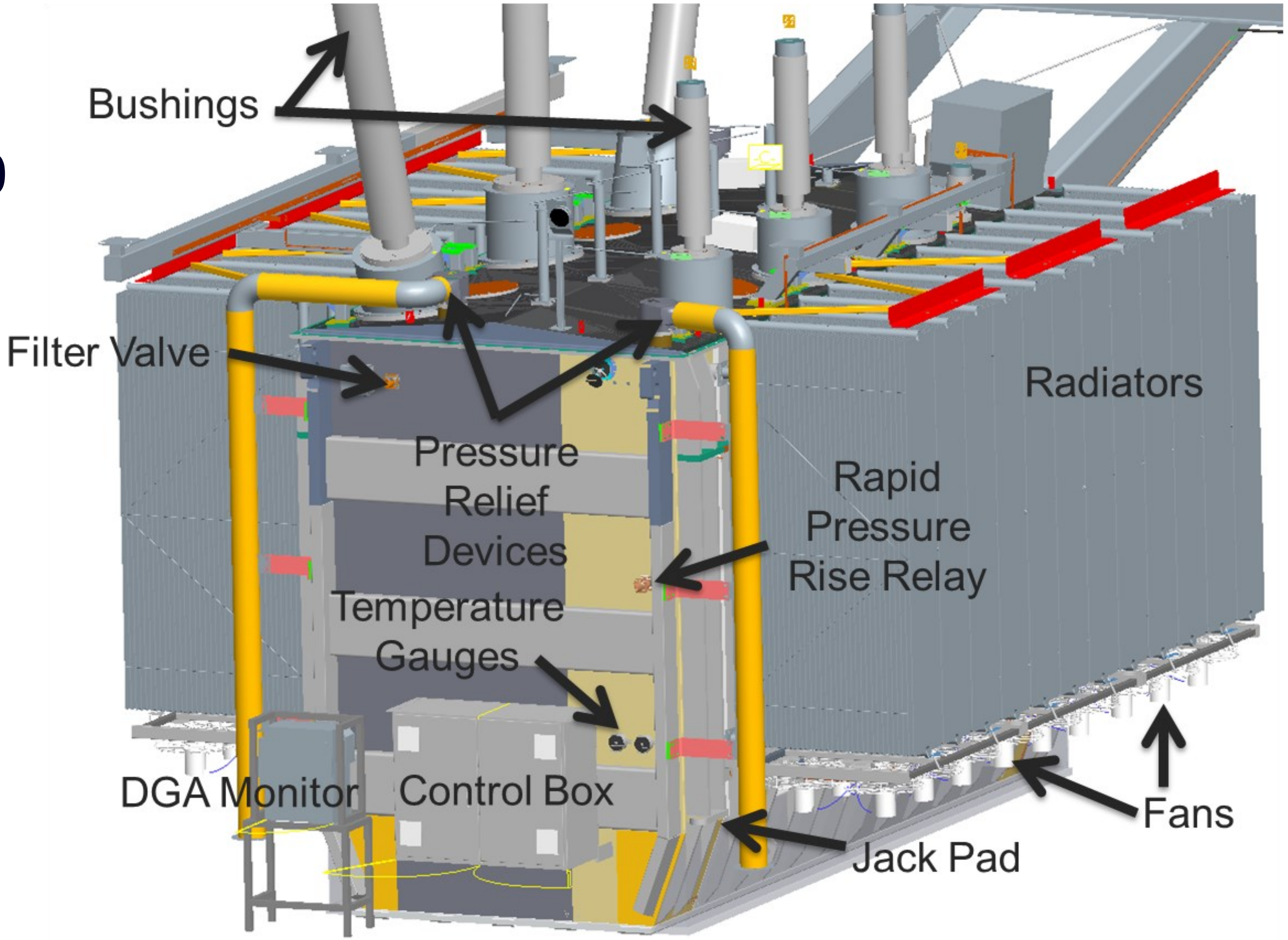
R...

0.8 3.83

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

Accessories

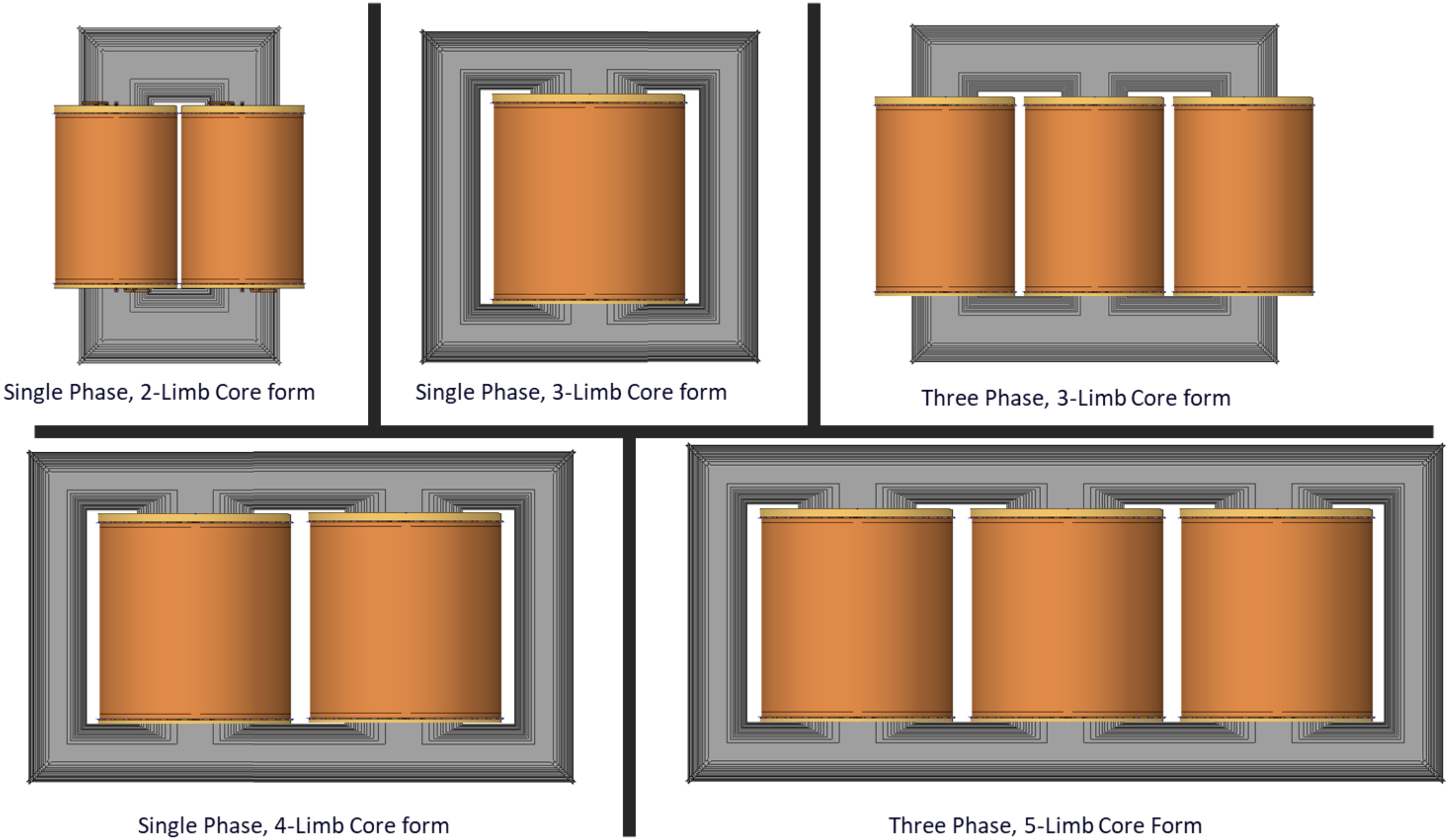
Accessories C57.12.10



Transformer Internals

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

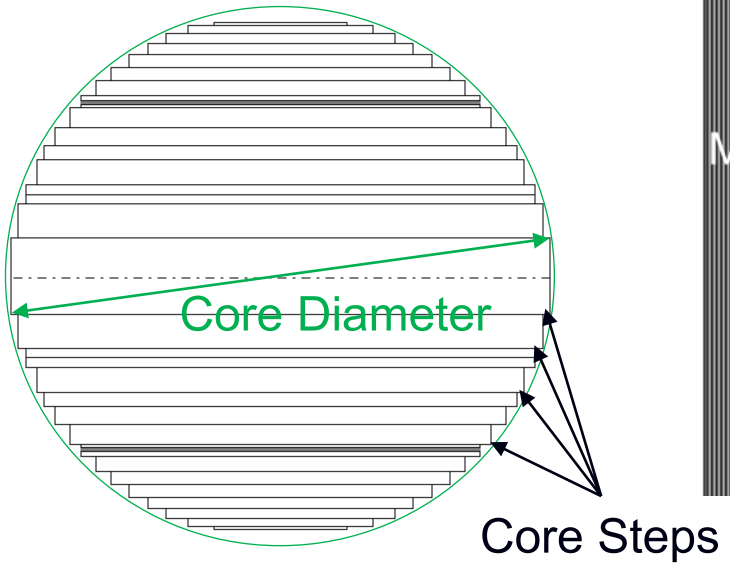
Different types of Core Construction

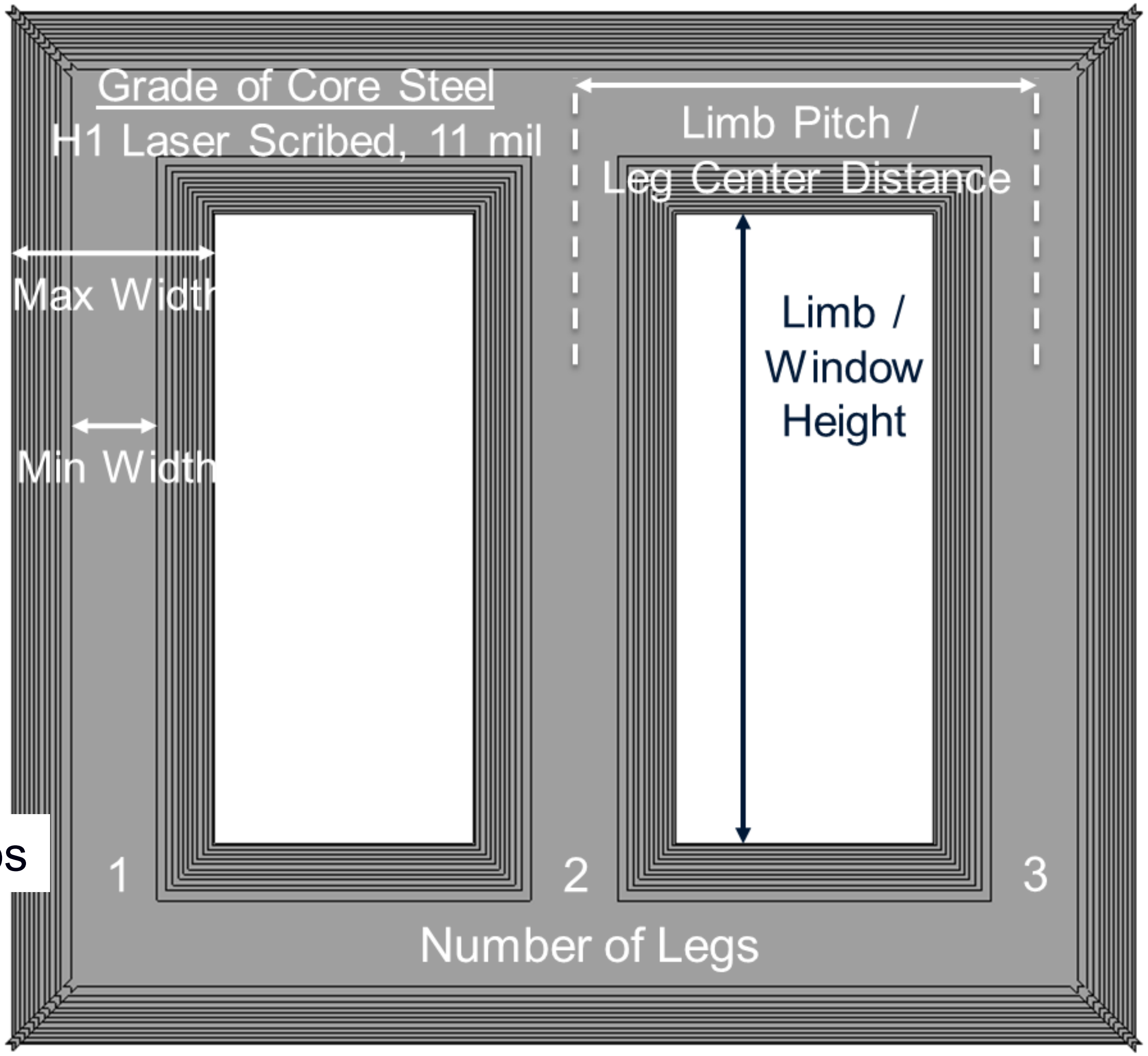


Core Parameters

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





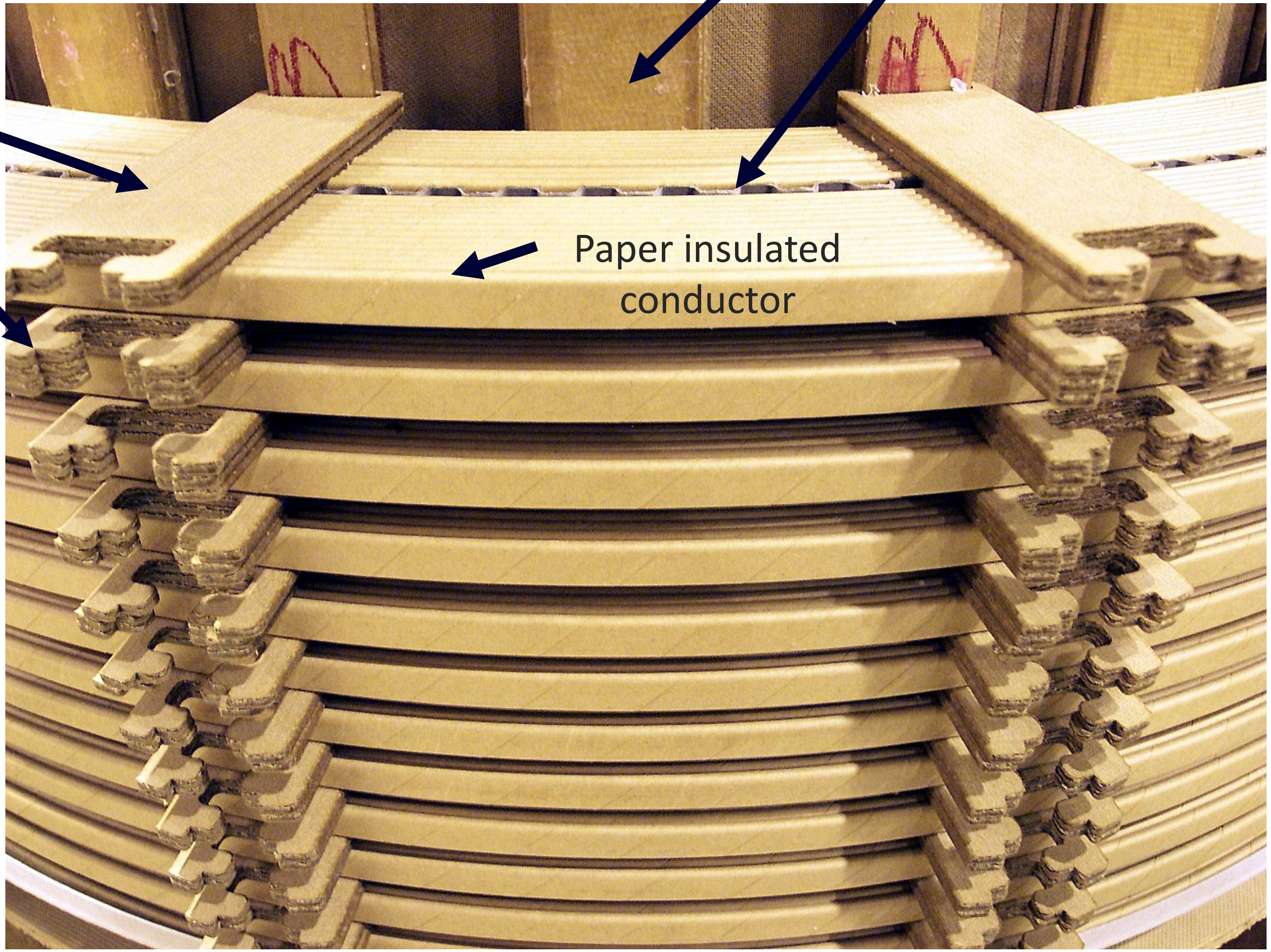
Types of Windings

Winding Types

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

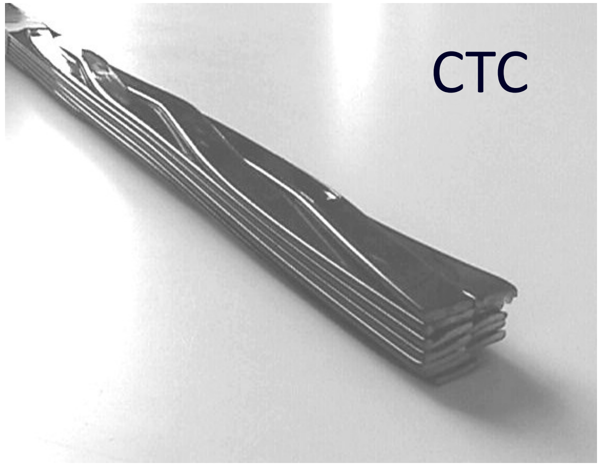
Above winding types may use magnet wire or CTC

Close up of Coil Construction (disc/screw)

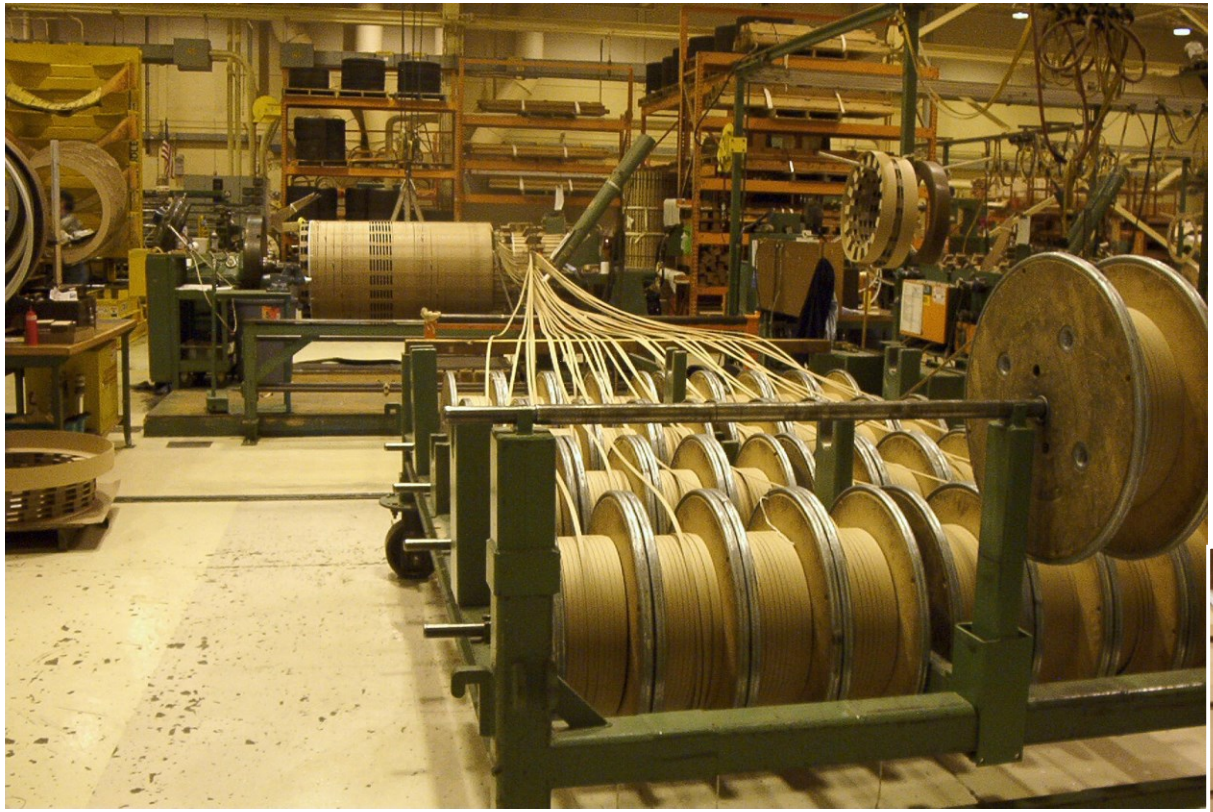


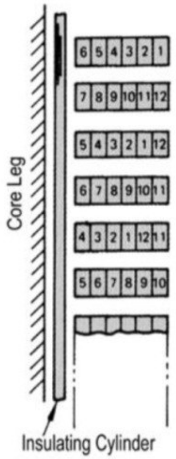
Type of conductors

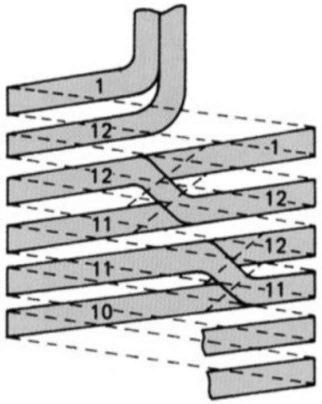
- Copper Strip or Foil
- Bus bar
- Rectangular wire (MW)
- Continuously Transposed Cable (CTC)



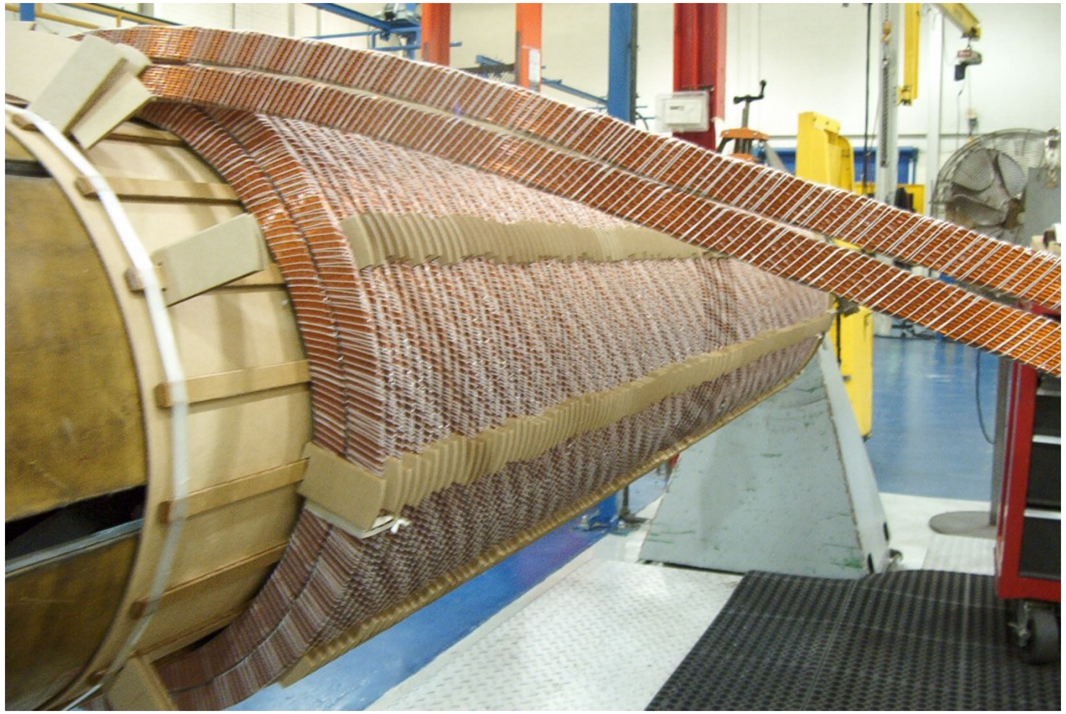
Helical / Screw (1 x 30 strands per turn)

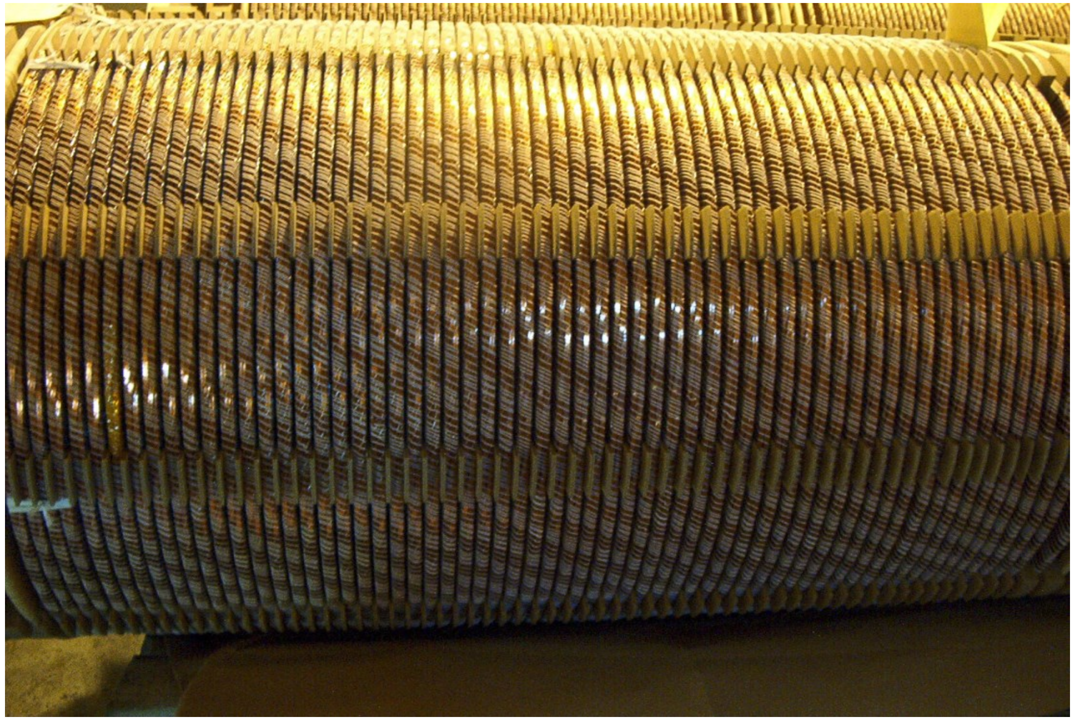






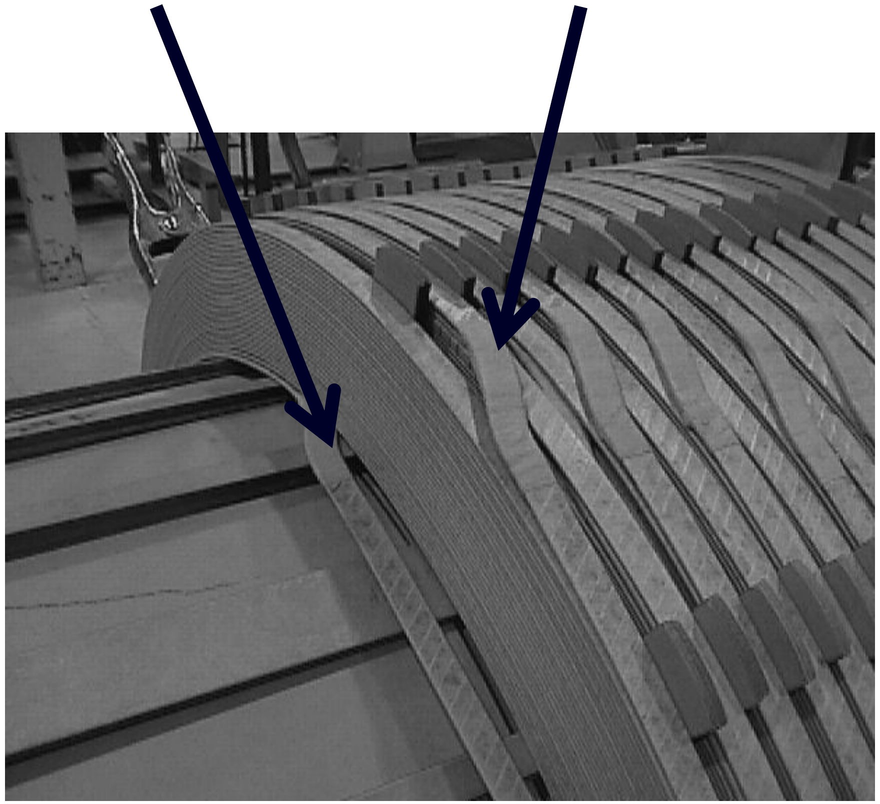
Helical Winding with two CTCs

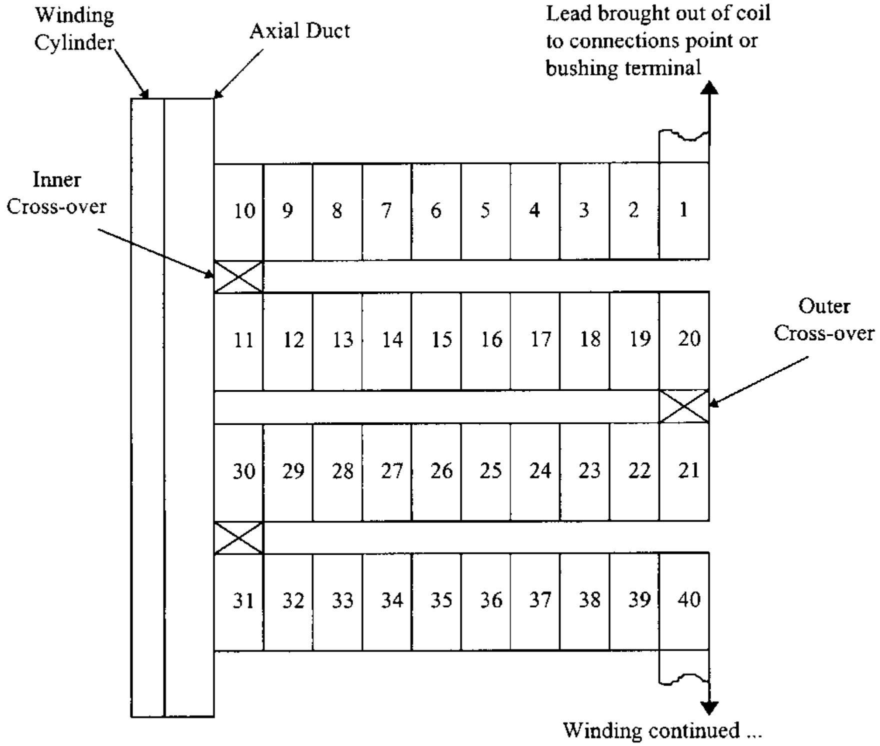




Continuous Disc Winding (1 strand per turn)

Inner cross-over Outer cross-over

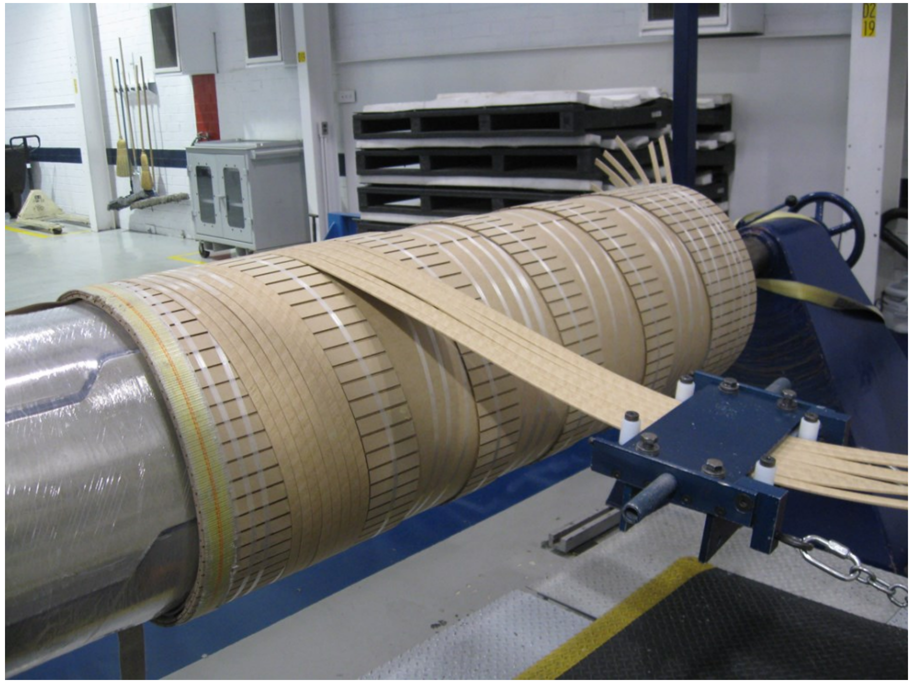




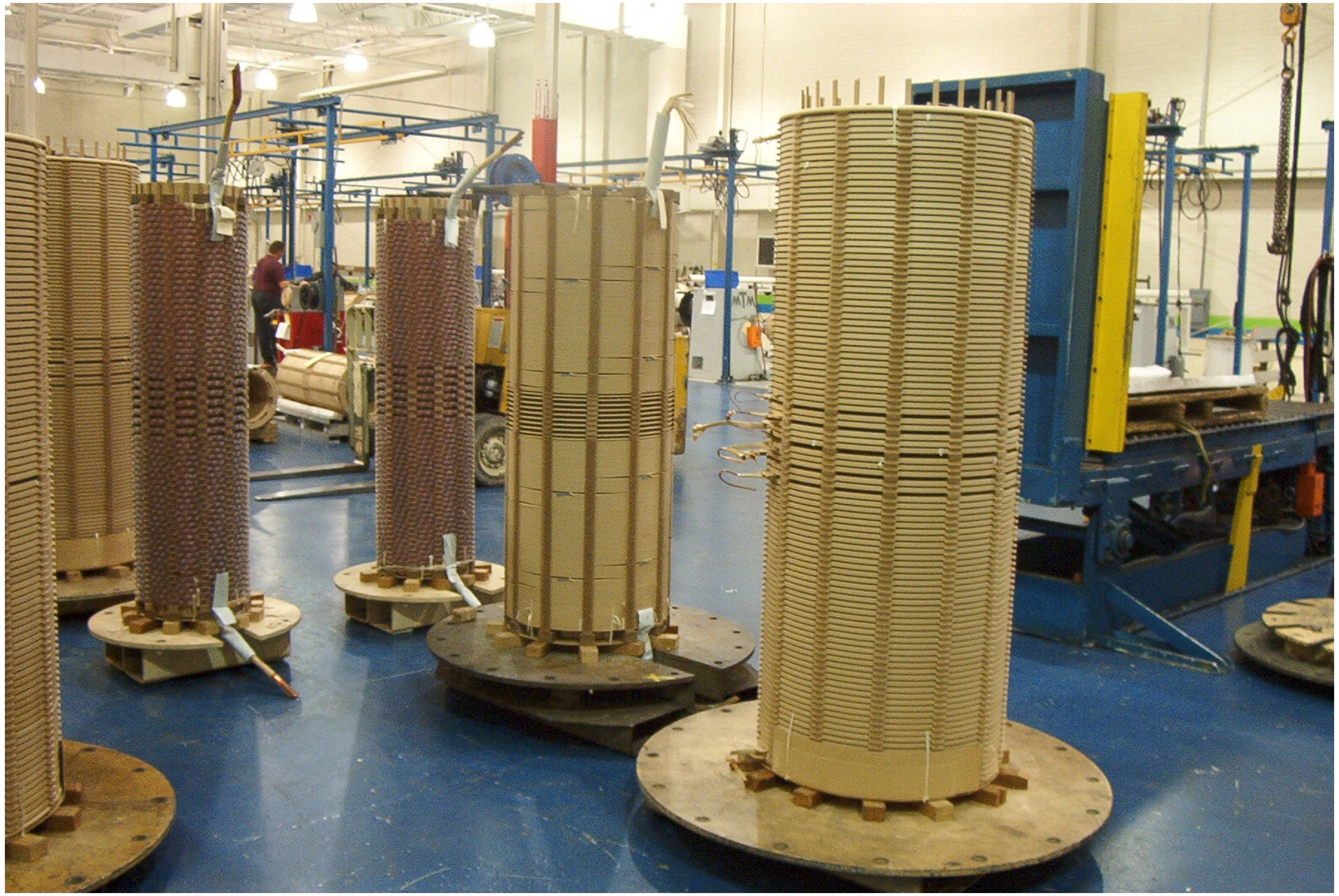
Disc Winding with Magnet Wires

Layer Type Winding

SLL / Layer / Barrel



Full Set of Windings



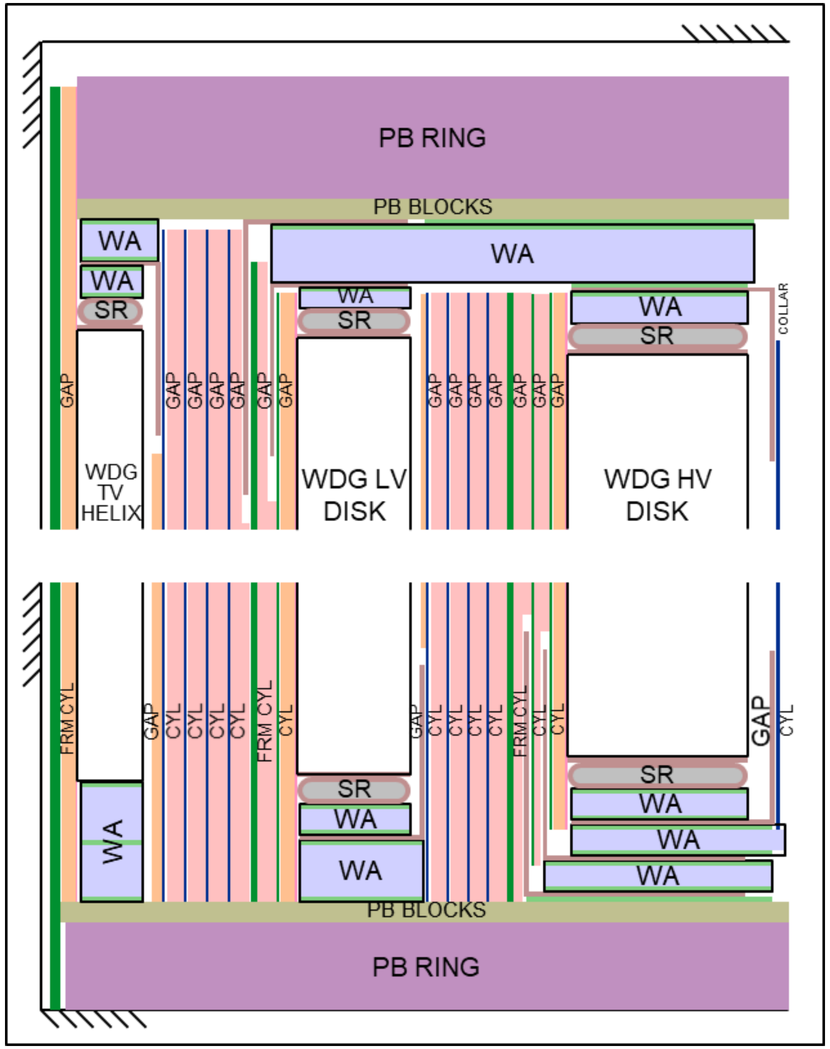
Insulation Materials

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



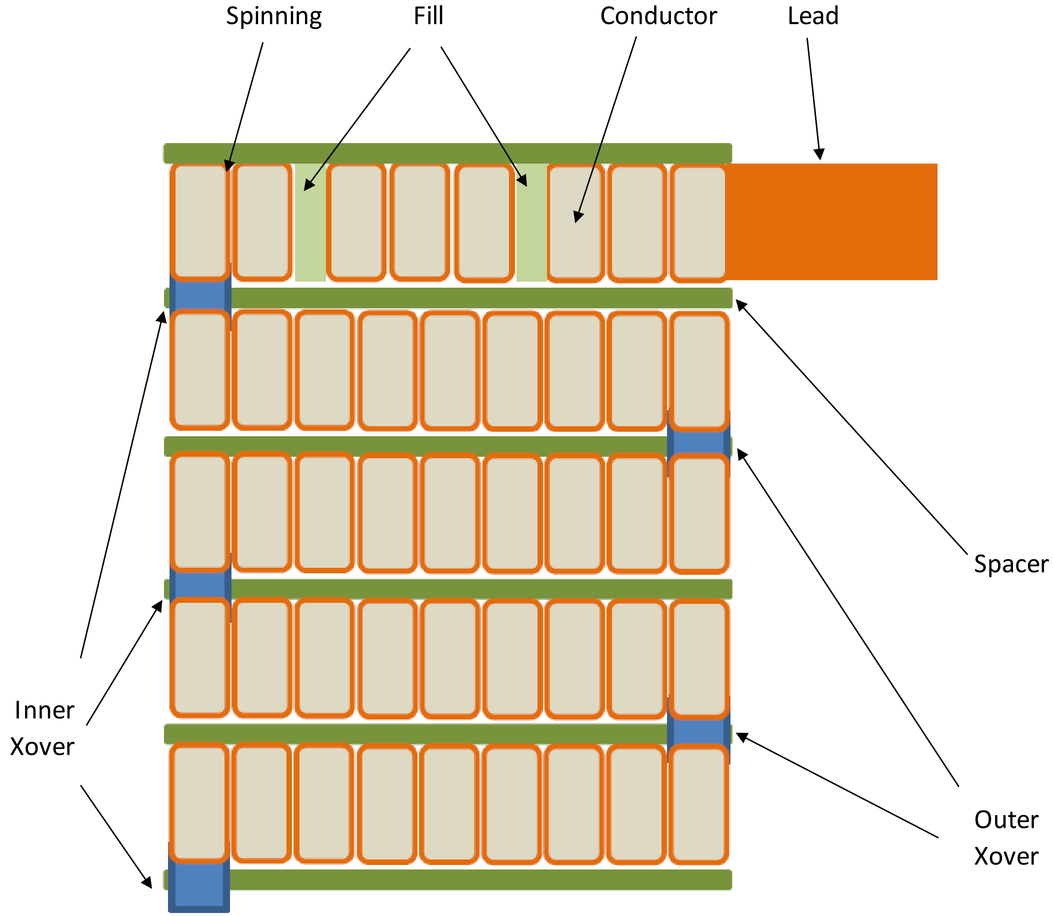
Insulation Materials

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

<u>Insulating Fluids</u>

- 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

<u>Other Materials</u>

Lead Insulation

- Kraft Paper
- Copaco
- Nomex
- Pressboard

Lead Supports

- Maple
- Laminated Wood
- TX2

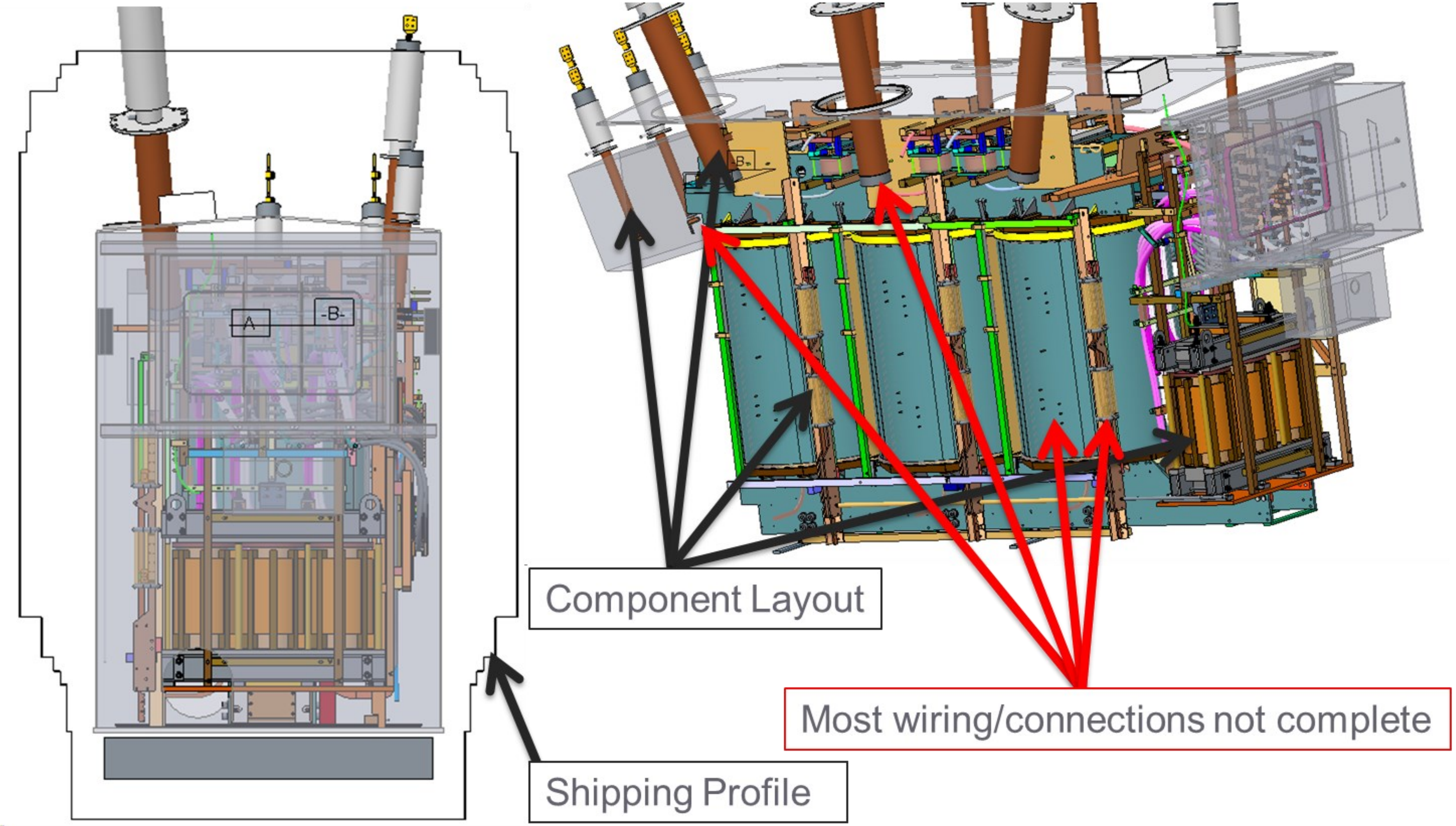
Bushings, Insulators

- Resin/epoxy materials
- Porcelain

Design Process

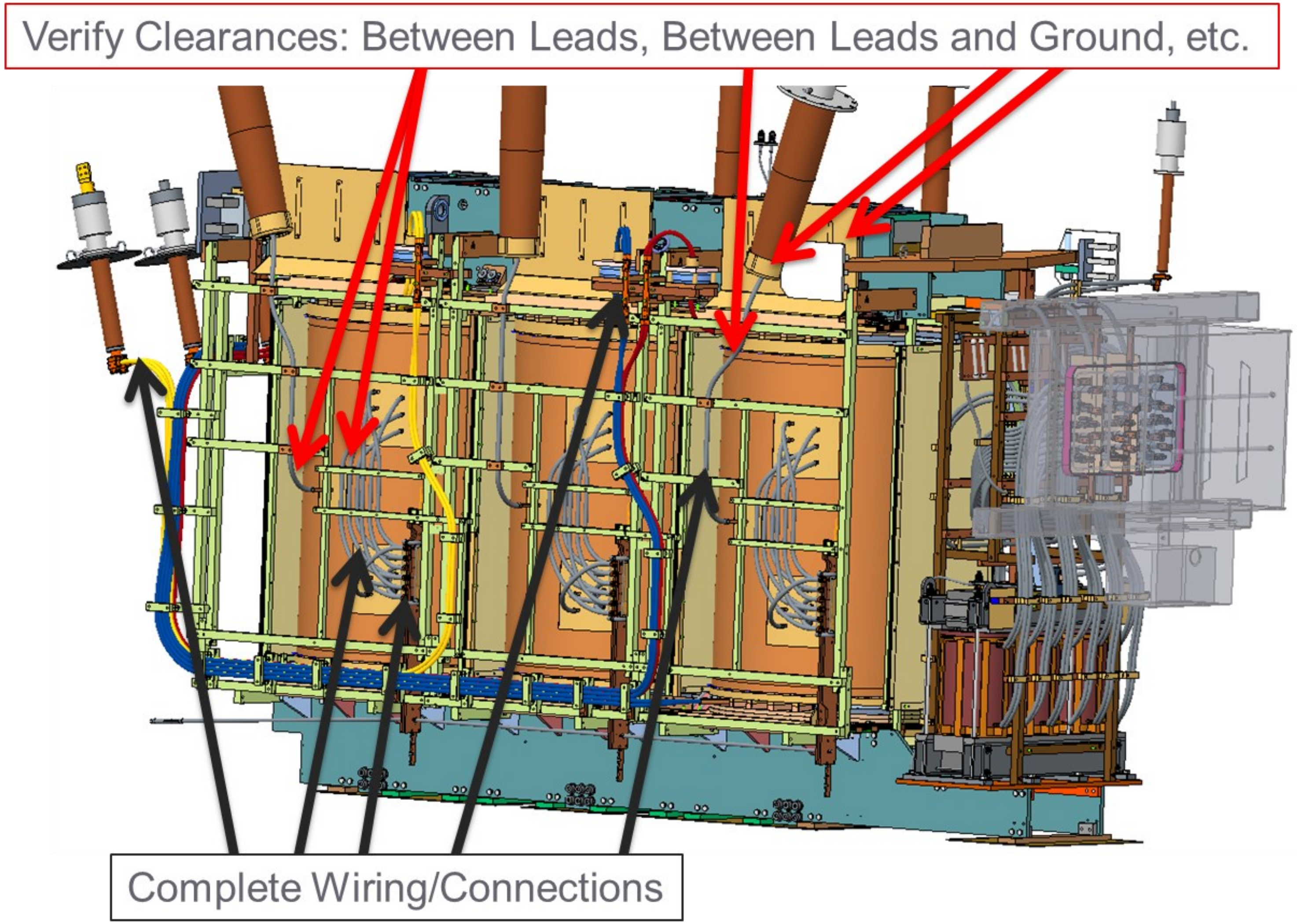
Internal Details

Tank Sizing



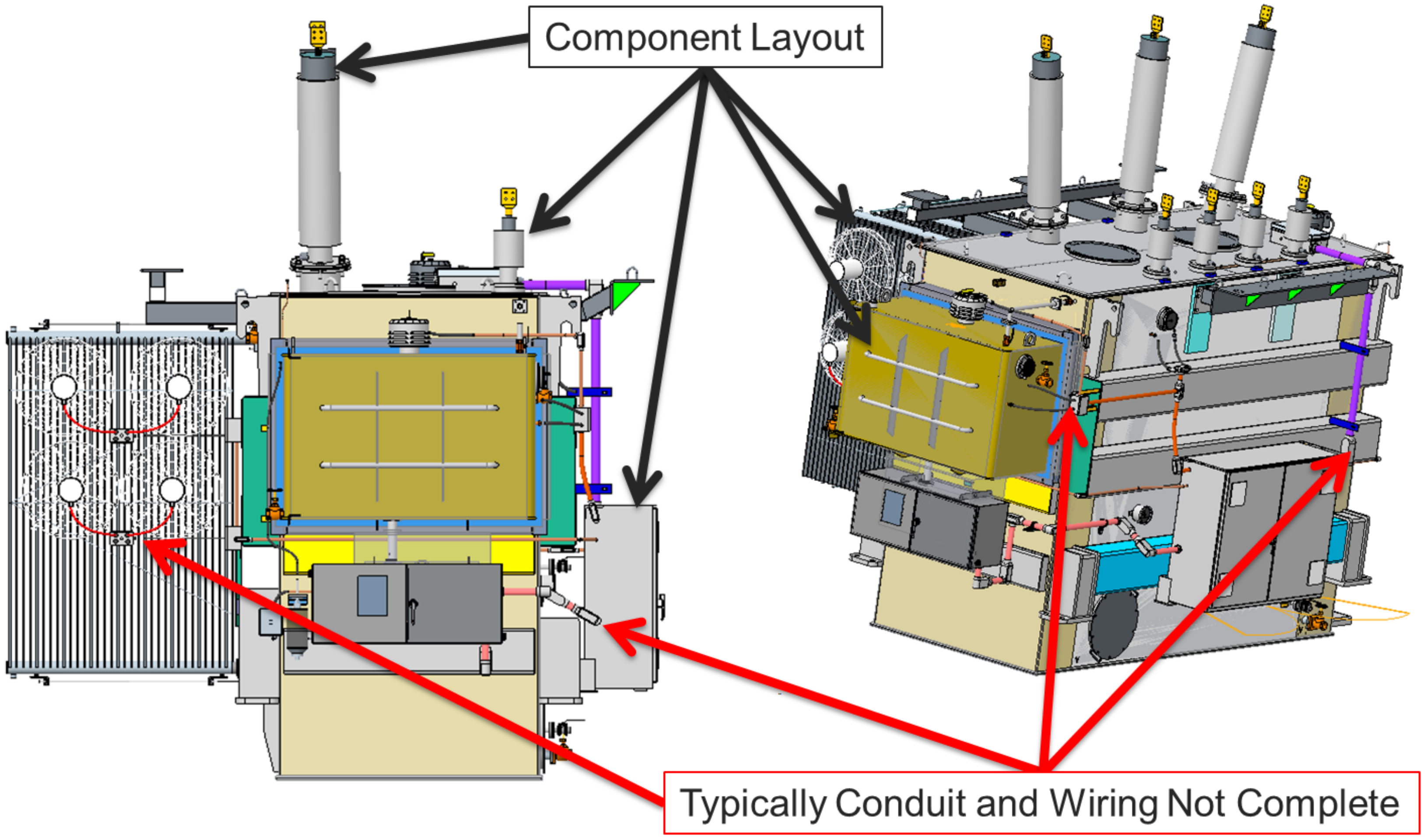
Internal Details

Finalize Design



External Details

Model to Generate
Outline Drawing

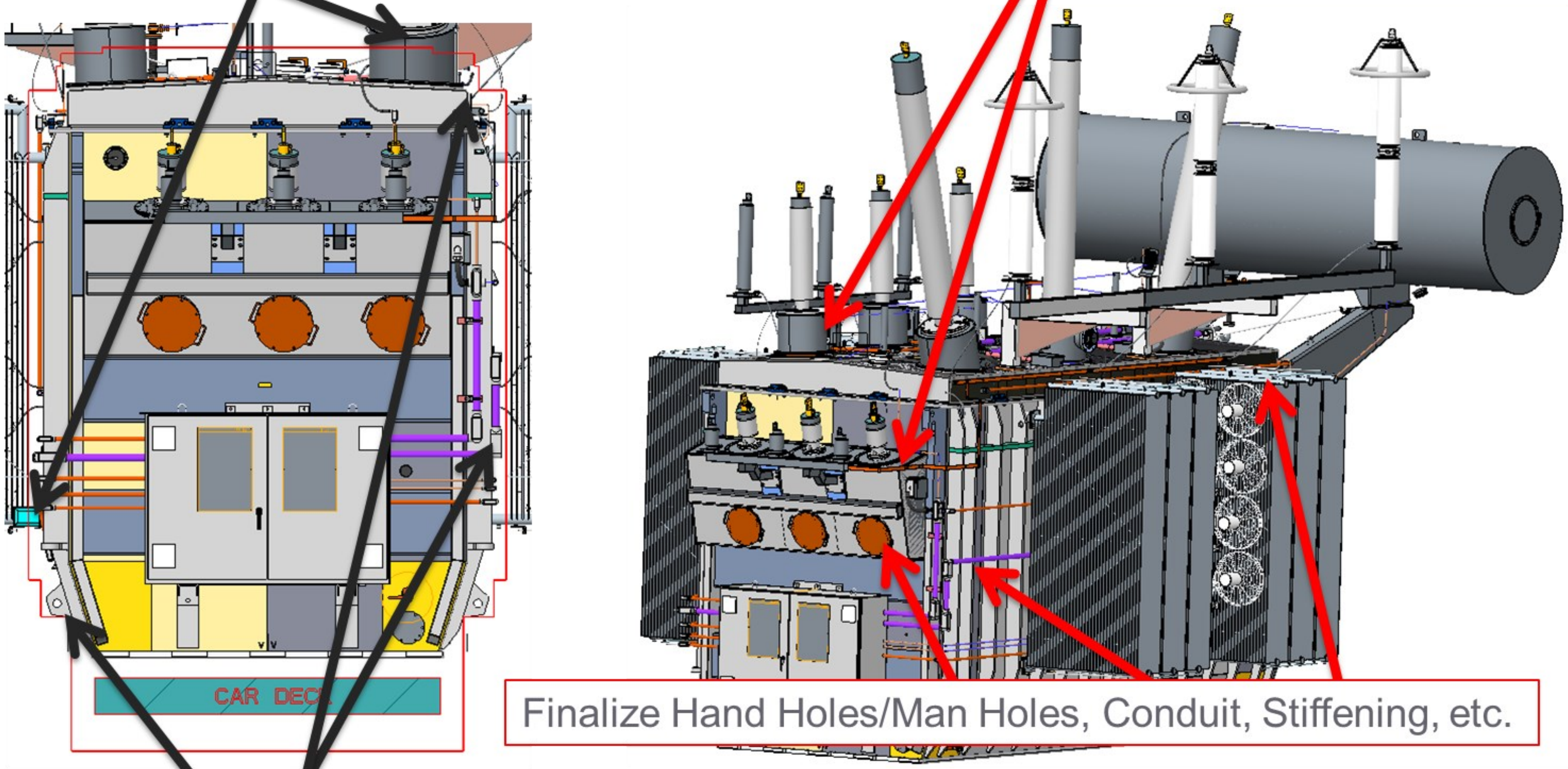


External Details

Finalize Design

Identify Items to be Removed for Shipping

Stainless Steel Where Required



Finalize Hand Holes/Man Holes, Conduit, Stiffening, etc.

Verify Components Fit in Shipping Profile

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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 Low Frequency (Power) Tests 1. Applied Potential 2. Induced Potential 3. RIV/Partial Discharge	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

Impact of Specification Requirements

Price Per MVA Concept.

- In view of the variations from spec to spec and all design parameters, cost per MVA becomes a complex equation. Example 20 mva , 138/13.8kv 6% impedance , 550 BIL and another 20 mva 138/13.8 kv 10 % impedance and 650 BIL will have different cost/price , losses .

- Therefore the first price of the transformer is based on MVA AND BIL and cost adders are needed for different characteristics.

- First price comprises of $P = S \times MVA^{X} + K\ BIL^{Y}$

a) Base Price
b) Addition for BIL
c) Other parameters per list below
d) Total Price

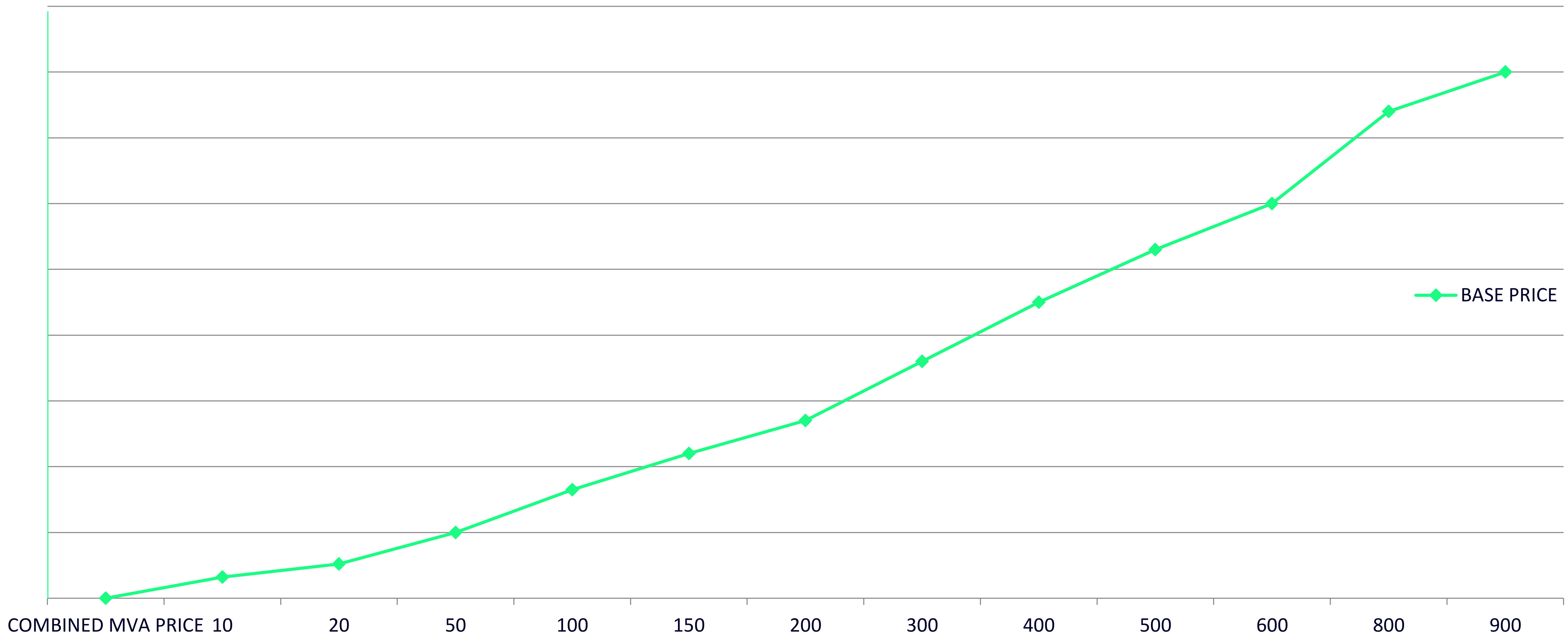
Parameters –Cost

a) Loss evaluation rates
b) Operating voltage , 138 kv delta vs 230 kv delta or Y
c) LTC type and cost, RMVI OR II ,In tank, tap range
d) Change in DETC or LTC range
e) Auto transformer co ratio (co ratio is used to calculate equivalent 2 winding rating for an auto transformer)
f) Change in temperature rise 55 Deg C vs 65 Deg C
g) Reduced sound level
h) Special dielectric tests impacting the clearances
i) Over excitation requirements , effects core size
j) Reduced PD levels
k) Reduced DGA Limits
l) Impedance ..high or low
m) Axially stacked windings
n) Unit AUX TR/ station AUX TR correction

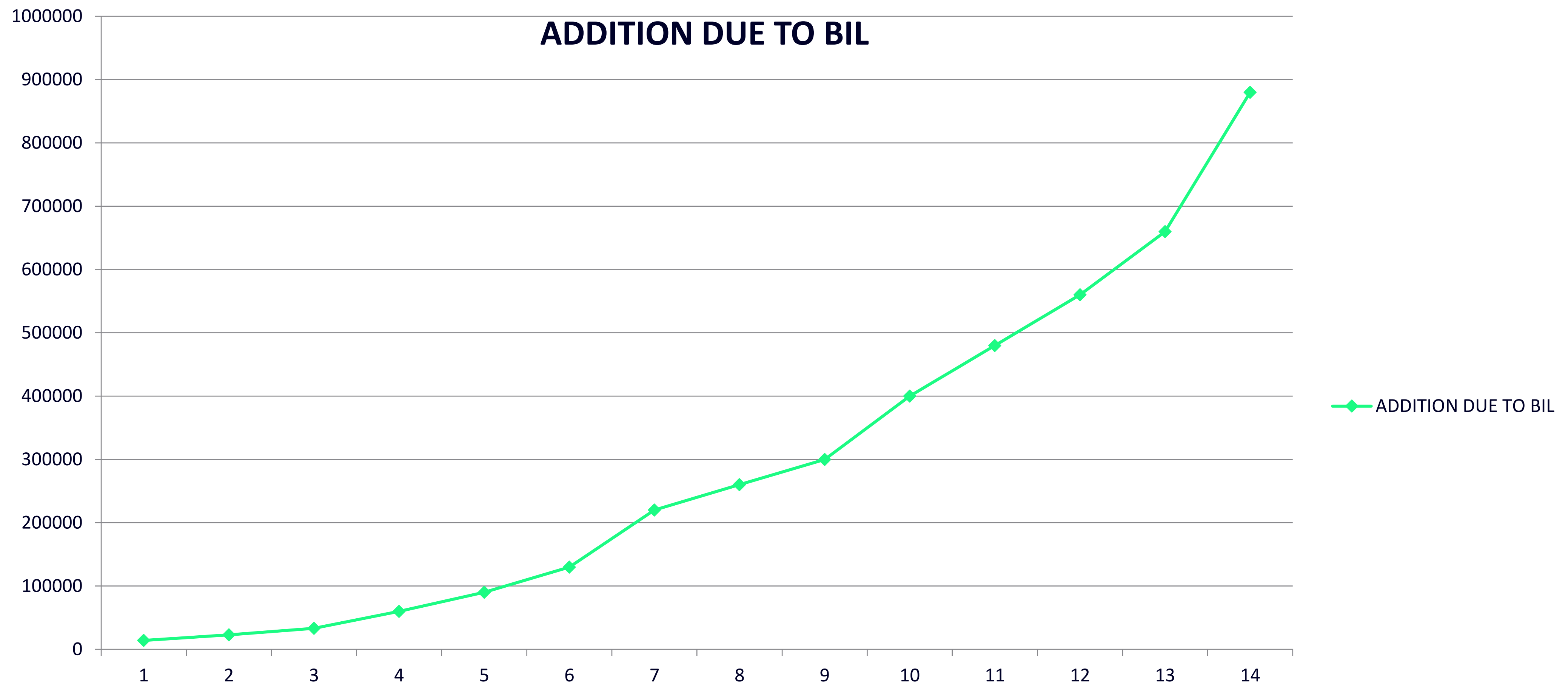
Parameters –Cost

a) No. of windings , if more than 3
b) Double layer RV windings
c) Unit with or series transformer
d) Cooling , ODAF, Overload , three winding loss
e) Tertiary ..loaded vs stabilizing mva . losses
f) Terminal boards cost /labor
g) Accessories cost
h) Special controls additions – Monitoring equipment
i) Bushings high voltage , high currents
j) Altitude
k) Short circuit requirements
l) Special current density/ flux density requirements
m) Application – Furnace , wind , wind solar , SCV , STATCOM
n) GIC Requirement
o) Reverse flow power
p) Paint thickness ,
q) CTs accuracy
r) specific make of accessories , control box

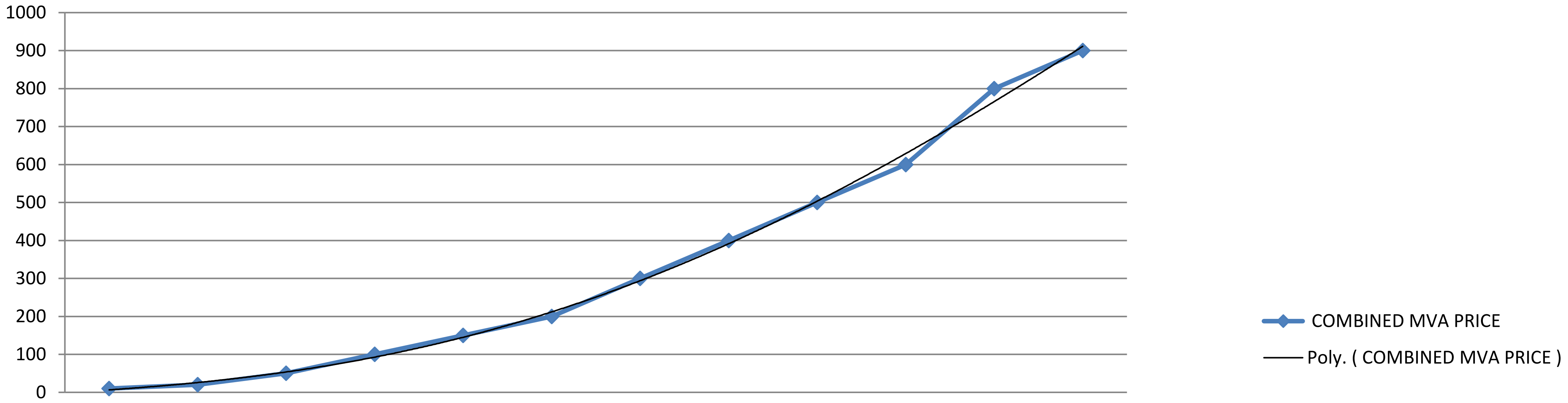
Base MVA Chart



Addition due to BIL change



Combined MVA+BIL



Questions

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