TRANSFODMER 101
Economics of Transformer Design

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Agenda

1. Loss Evaluation /TOC
2. Typical Specification parameters
3. Design and construction materials
4. Impact of specification requirements
5. Test Requirements
6. Others

If you have questions, please stop and ask at ANY time during the presentation

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Loss Evaluation

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User Parameters

- $/KW No Load Loss at 100% Excitation
- $/KW Load Loss at 100% Self Cooled KVA
- $/KW Auxiliary Losses per Forced Cooled Stage

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Loss Evaluation

Manufacturers Guarantee Values

- Selling Price
- No Load Loss at 100% Excitation
- Load Loss at 100% Self Cooled Rating
- Auxiliary Losses per Stage of Forced Cooling

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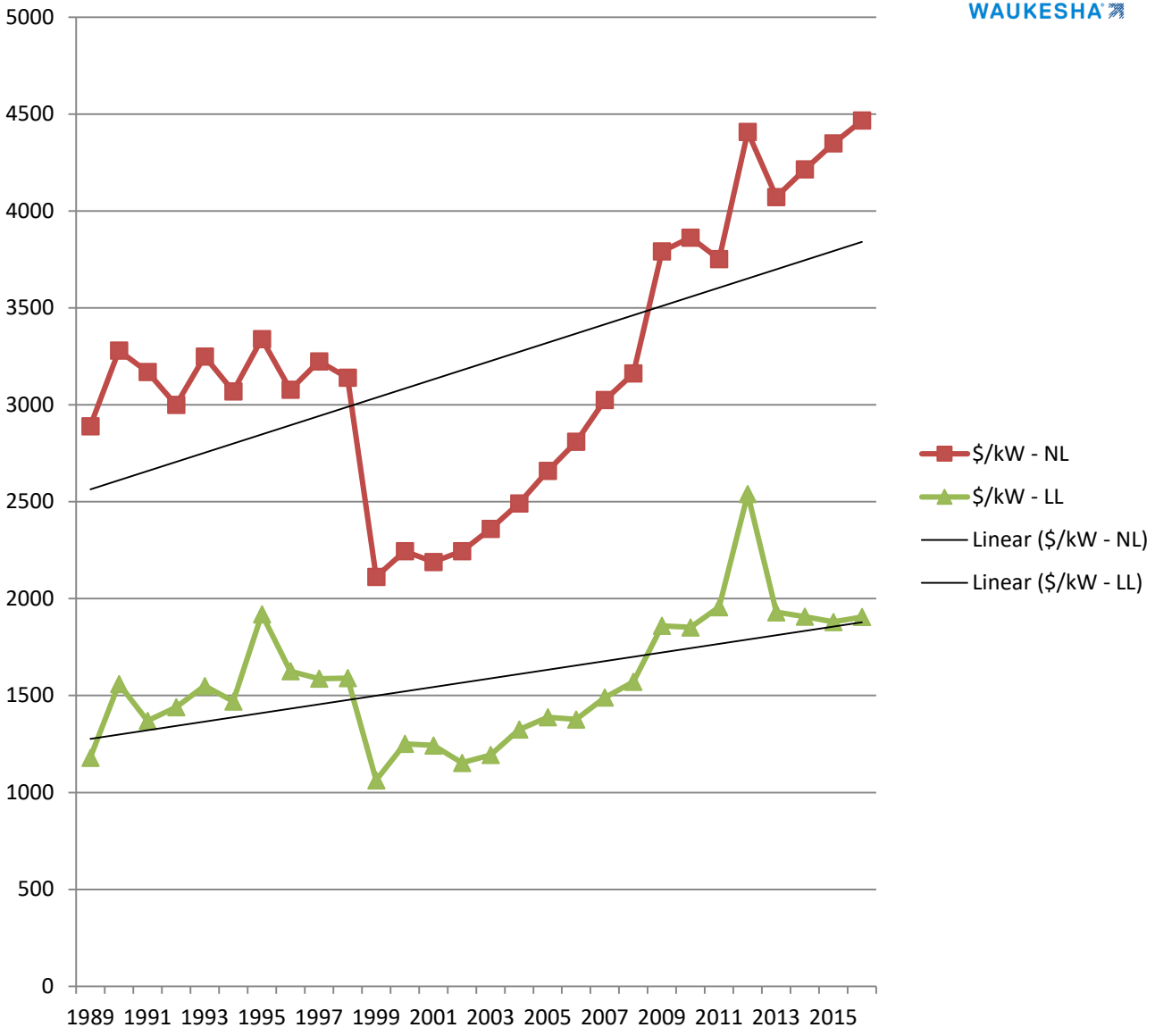
Loss Evaluation Trend

Year	$/kW - NL	$/kW - LL
1989	2890	1180
1990	3280	1560
1991	3170	1370
1992	3000	1440
1993	3250	1550
1994	3070	1470
1995	3340	1920
1996	3078	1626
1997	3225	1587
1998	3140	1590
1999	2113	1063
2000	2245	1251
2001	2190	1243
2002	2245	1153
2003	2360	1194
2004	2492	1325
2005	2659	1388
2006	2810	1377
2007	3025	1490
2008	3162	1571
2009	3792	1860
2010	3863	1852
2011	3752	1957
2012	4408	2540
2013	4073	1930
2014	4215	1907
2015	4349	1880
2016	4467	1906



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20 MVA 132/13.8 KV – Evaluation

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Load Loss $2000/kw, No Load Loss $3000/kw

Vendor A

- Price: $500,000
- No load loss: 20 kw
- Load loss+Aux Loss: 100kw
- Loss Evaluation: BASE
- TOC: $500,000

Vendor B

- Price: $475,000
- No load loss: 23 kw
- Load +Aux Loss: 110 kw
- Loss Evaluation: $29,000
- TOC: $504,000

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Guides for Loss Evaluation

Distribution Transformers

- "A Method for Economic Evaluation of Distribution Transformers" Report of the EEI Task Force on Distribution Transformer Evaluation" April 1981
- "Guide for Evaluation of Distribution Transformers - Parts I & II" GE Industrial & Power Systems, September 1994 and References contained therein
- Several energy efficiency programs now in place (NEMA, DOE, etc.)

Power Transformers

- ANSI/IEEE C57.120 "IEEE Loss Evaluation Guide for Power Transformers and Reactors" and references in its bibliography

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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

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

ADDITIONAL TAP VOLTAGES

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

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

R...				
0.8	3.83			

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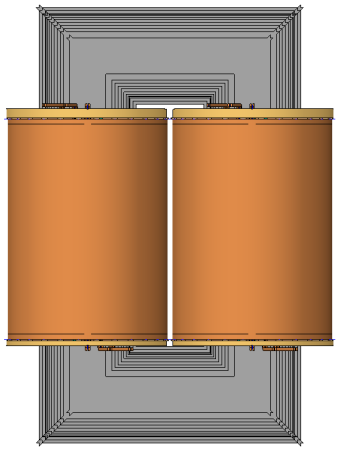
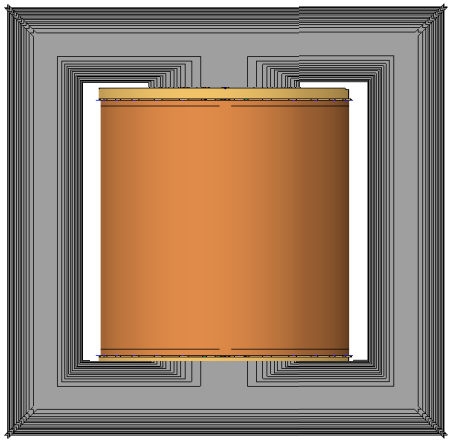
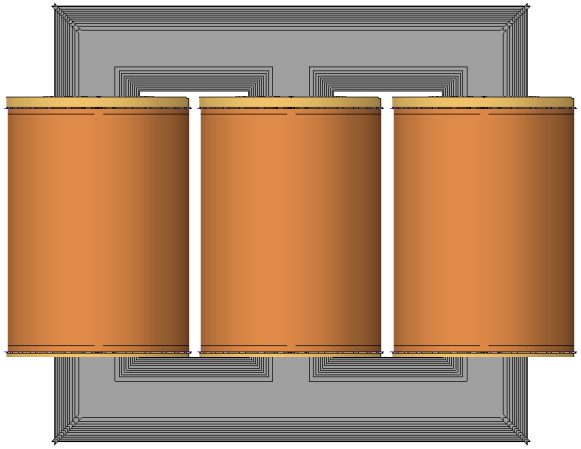
Different types of Core Construction



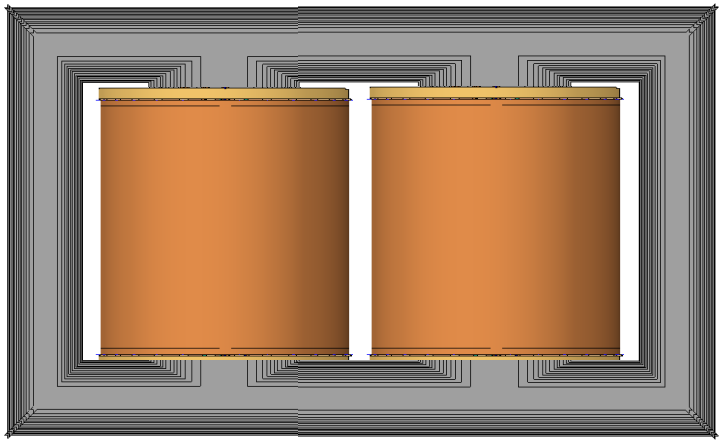
Single Phase, 2-Limb Core form



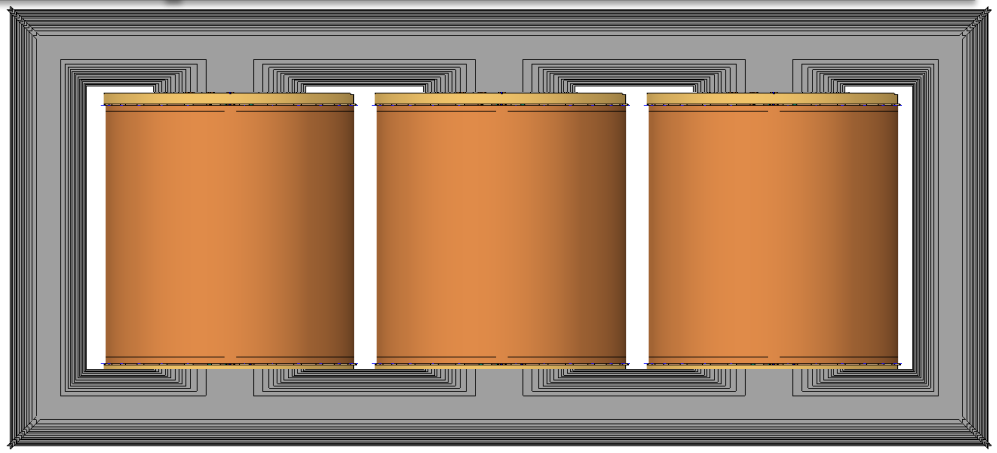
Single Phase, 3-Limb Core form



Three Phase, 3-Limb Core form



Single Phase, 4-Limb Core form



Three Phase, 5-Limb Core Form

Core Types

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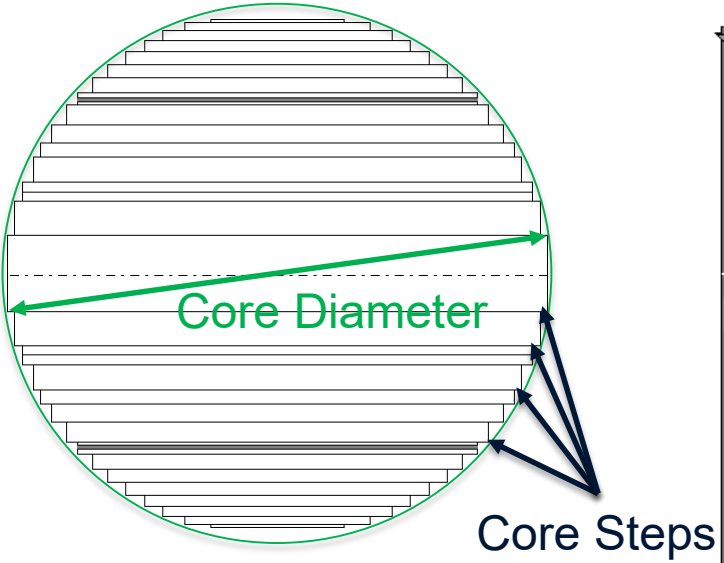
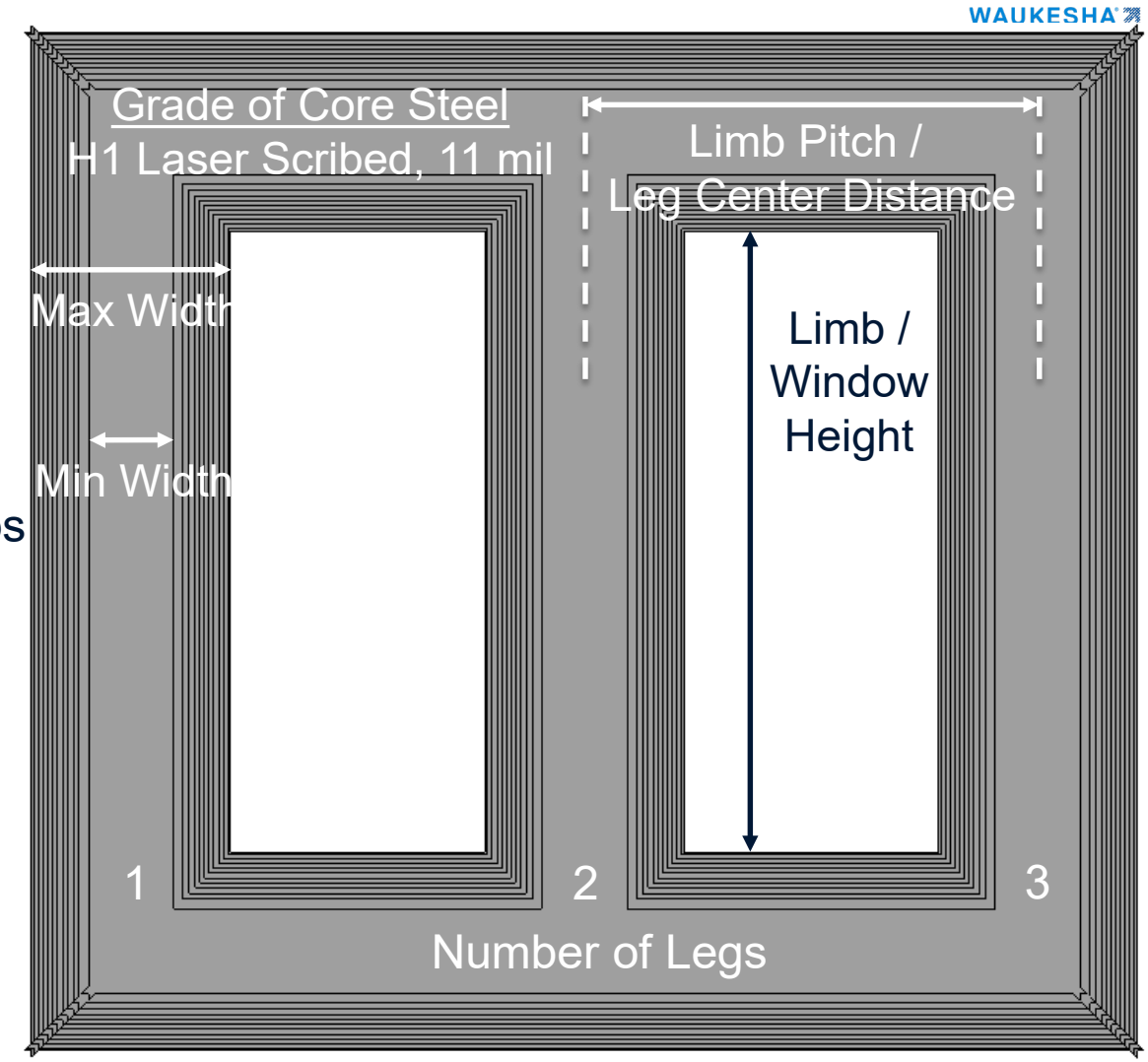
Core Design Considerations





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

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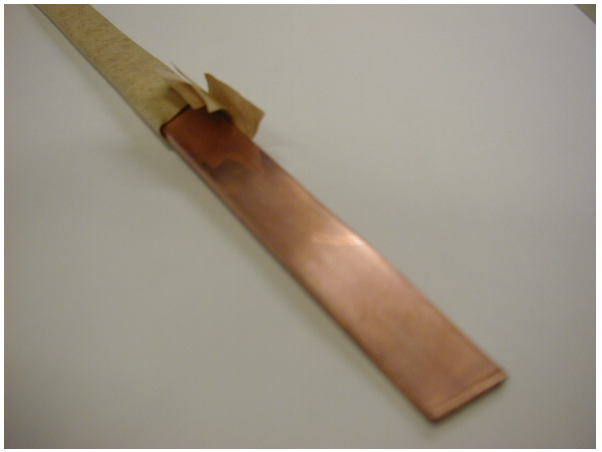
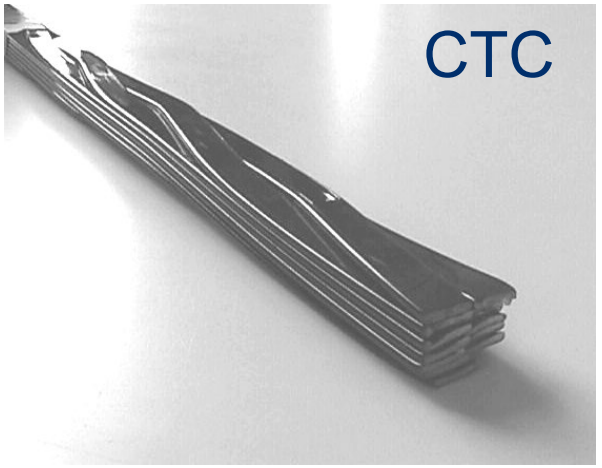
Type of Conductors

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





Conductor Selection

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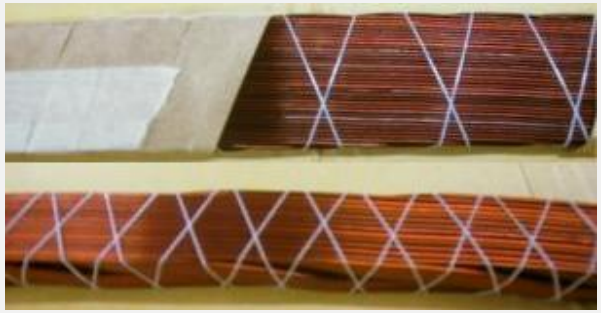
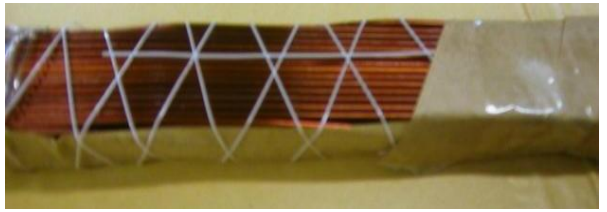
Type of Conductors

ARRANGEMENT	APPLICATION	PICTURE
• CORDEX only with protection paper	• LV or TV winding	
• CORDEX1 with 2 layers papers at the bottom in radial dimension	• LV winding when its better to split CTC in two due to the big radial dimension	
• CORDEX2 with 2 layers papers in axial dimension	• Layer winding	
• CORDEX3 with aramid paper at the bottom in radial dimension	• HV disk winding	

Conductor Selection

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Types of Windings

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Winding Types

Layer/Barrel

- Regulating (RV) and Tertiary windings (TV)

Screw (Helical)

- LV, Series (Booster) transformer

Continuous Disc

- HV, LV, Series (Booster)

Above winding types may use magnet wire or CTC

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Layer Type Winding

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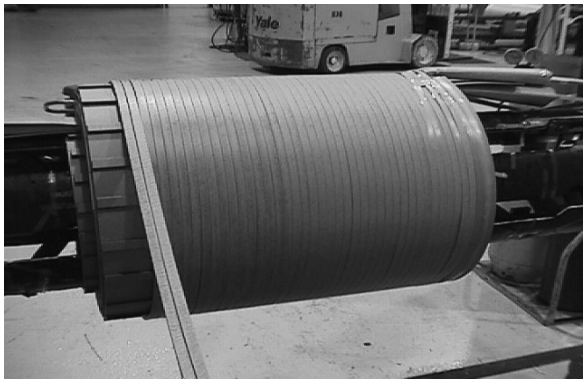
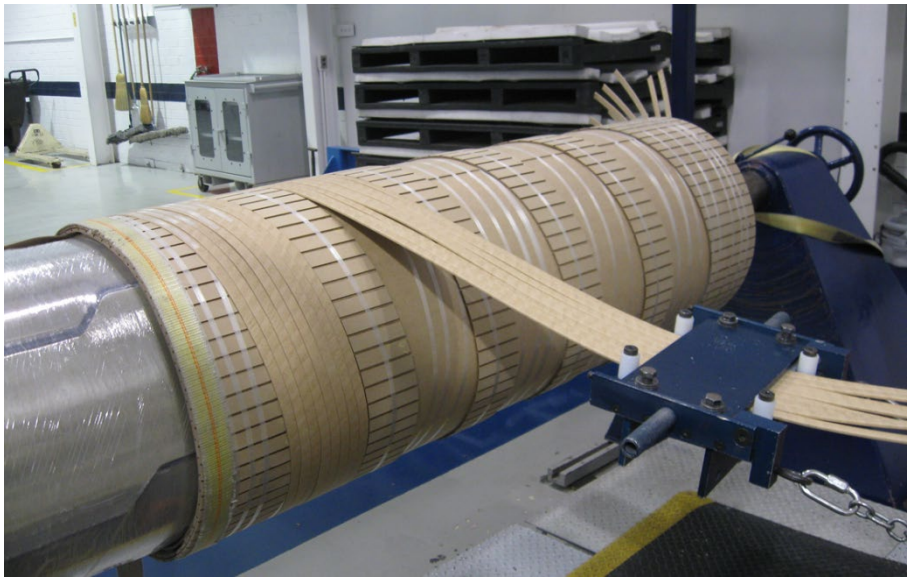
SLL / Layer / Barrel





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SLL / Layer

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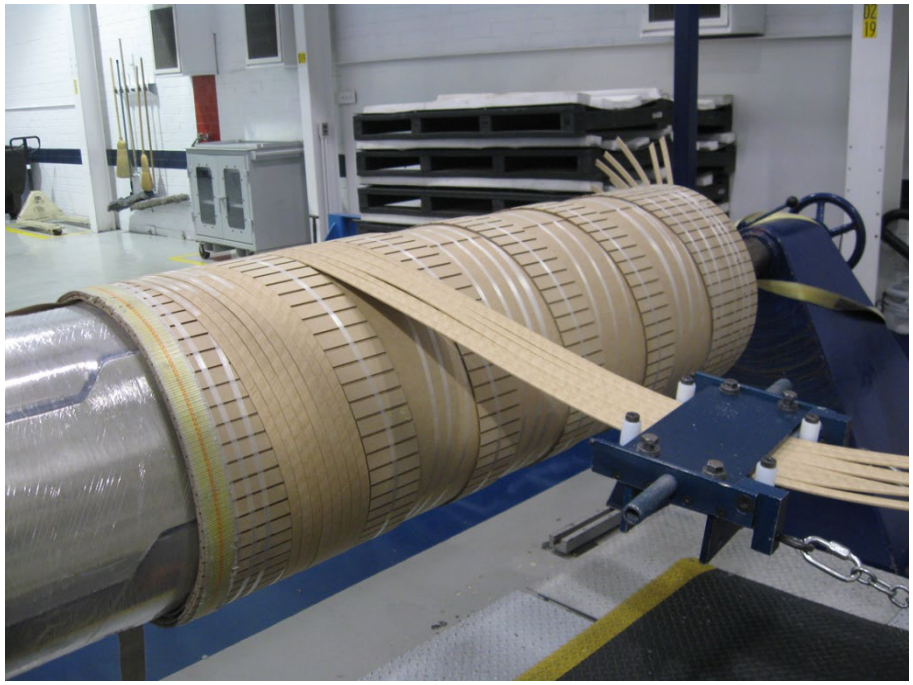
SLL / Layer / Barrel



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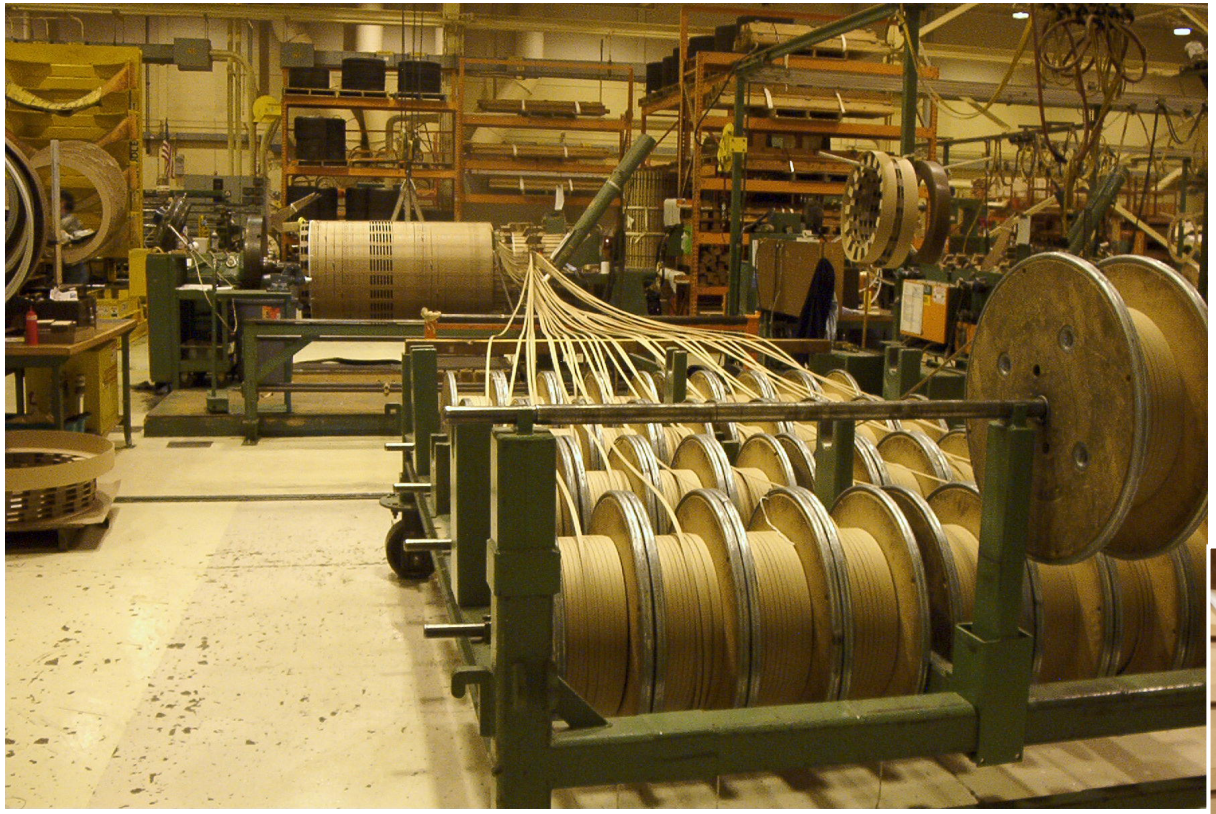
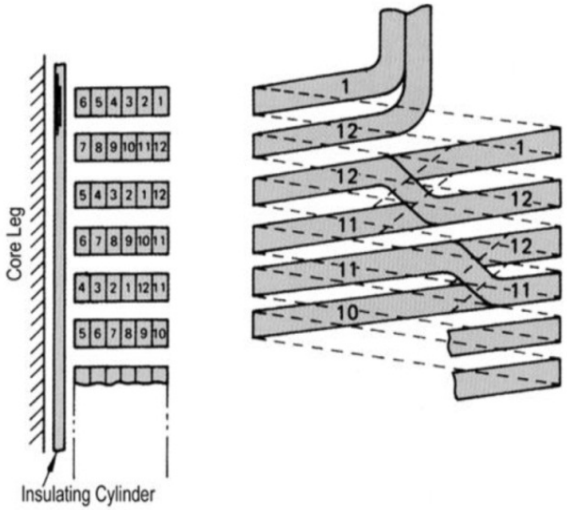
Helical / Screw





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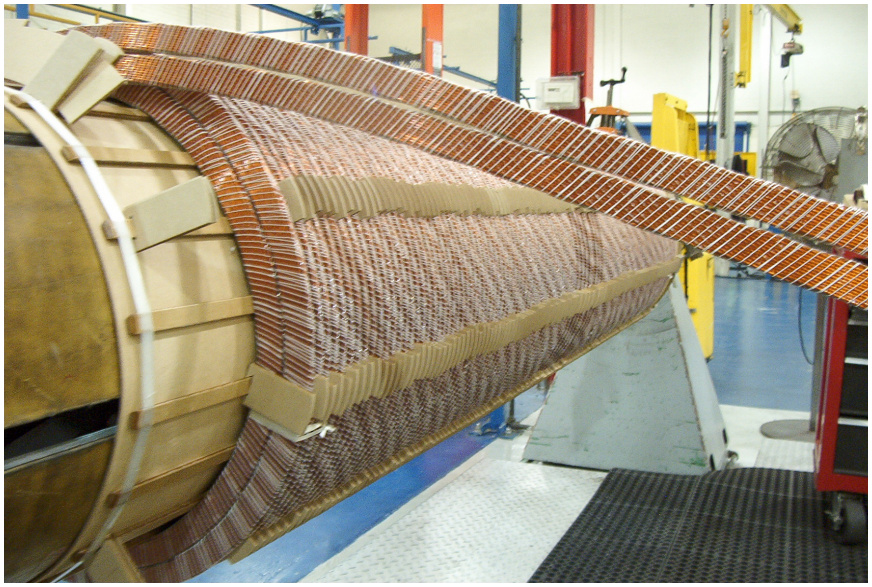
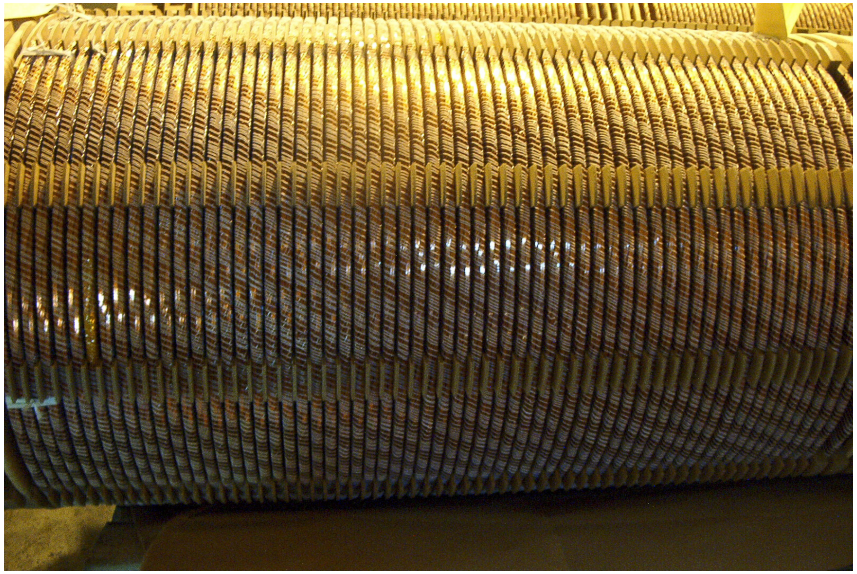
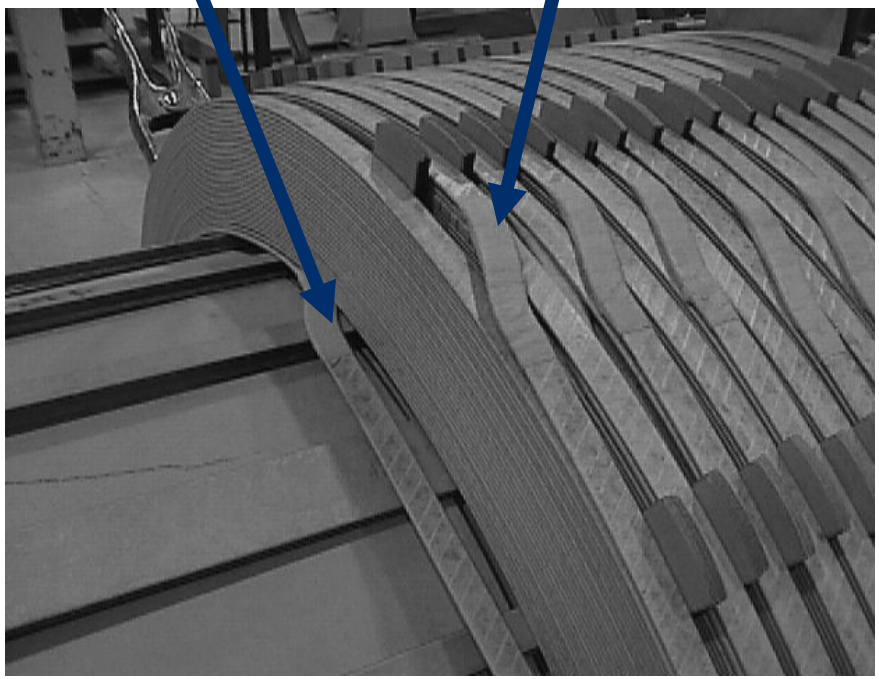
Helical Winding with two CTC's

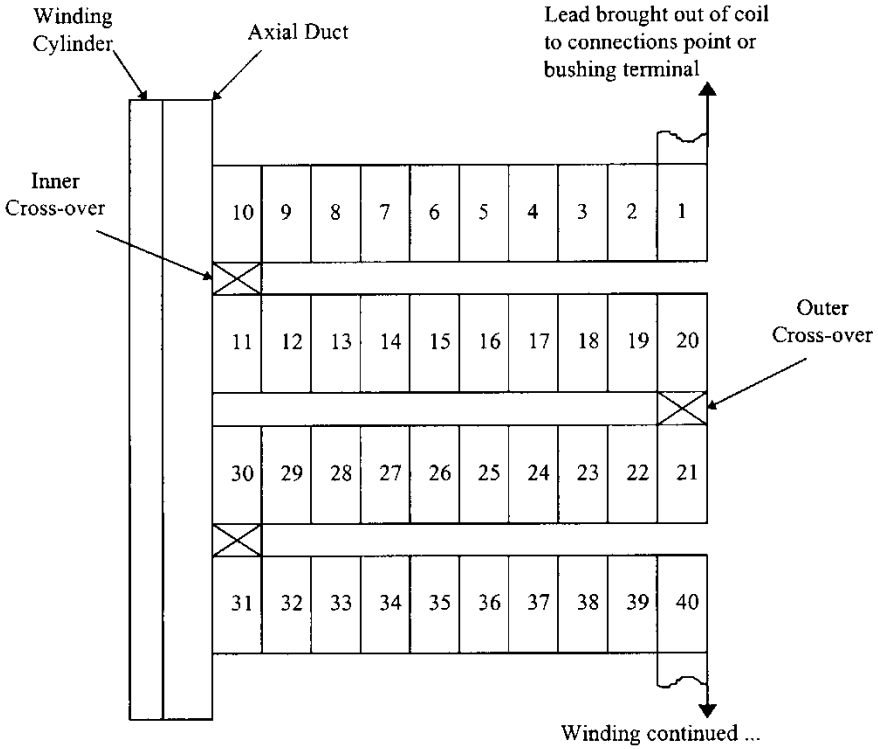




Continuous Disk Winding

Inner cross-over Outer cross-over





Winding Selection

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Disc Winding with Magnet Wires

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Winding Selection

Set of Windings

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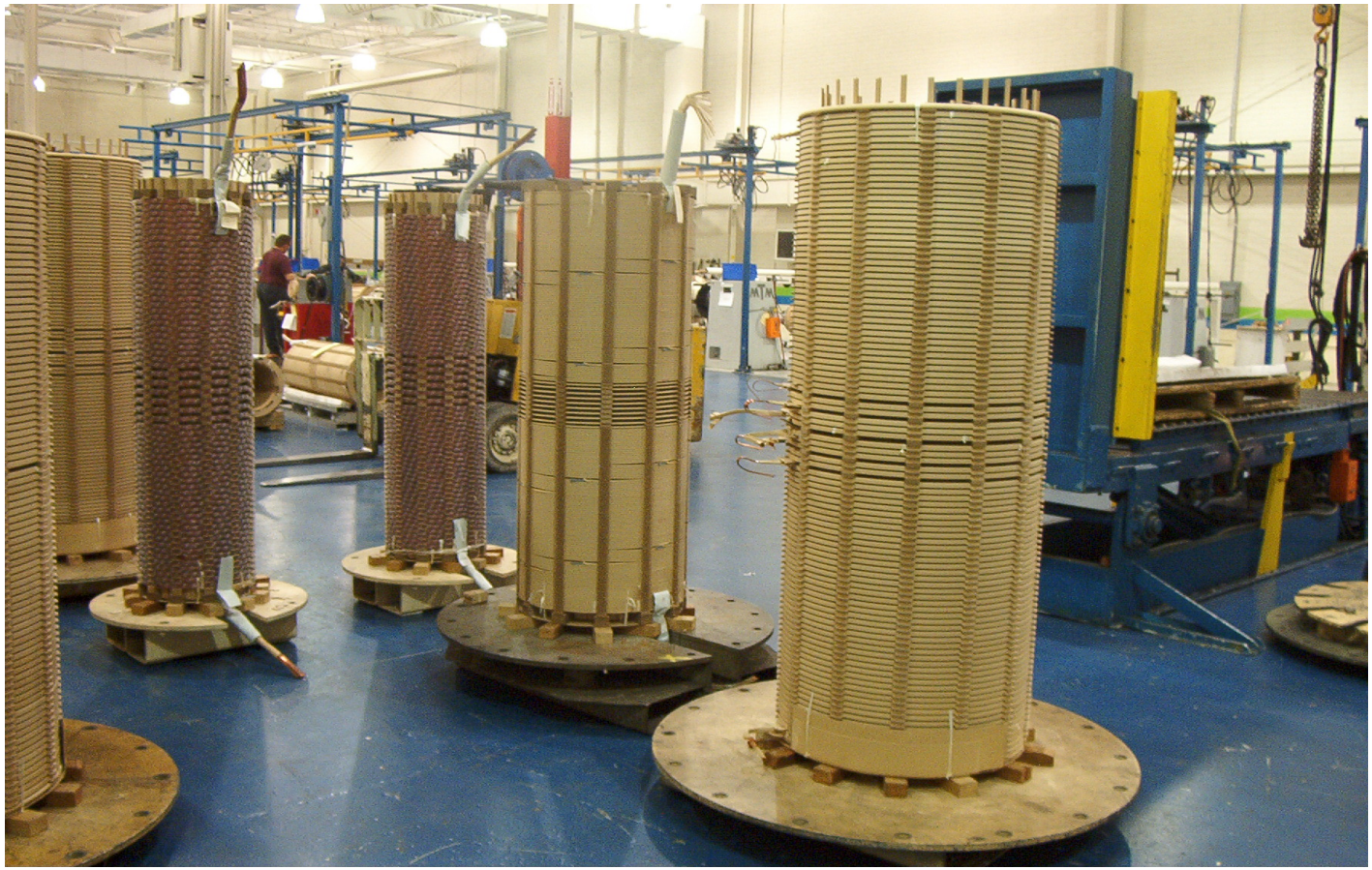
Set of Windings for a given Transformer



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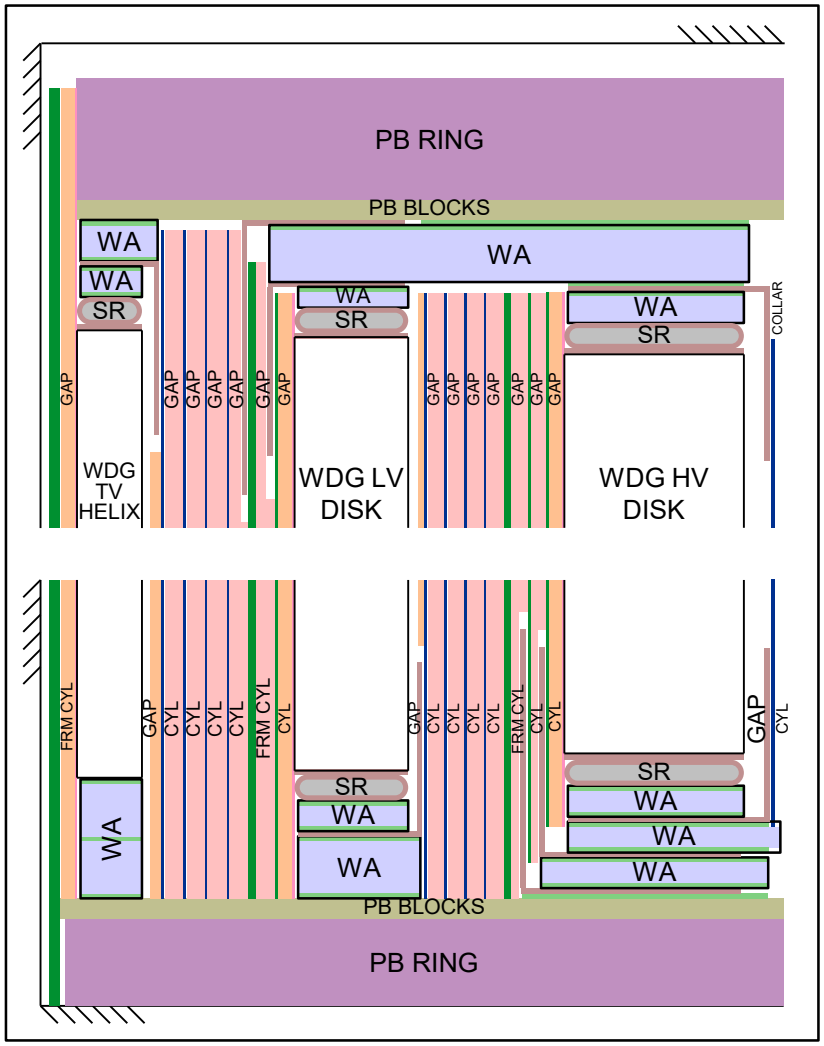
Insulation Materials

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



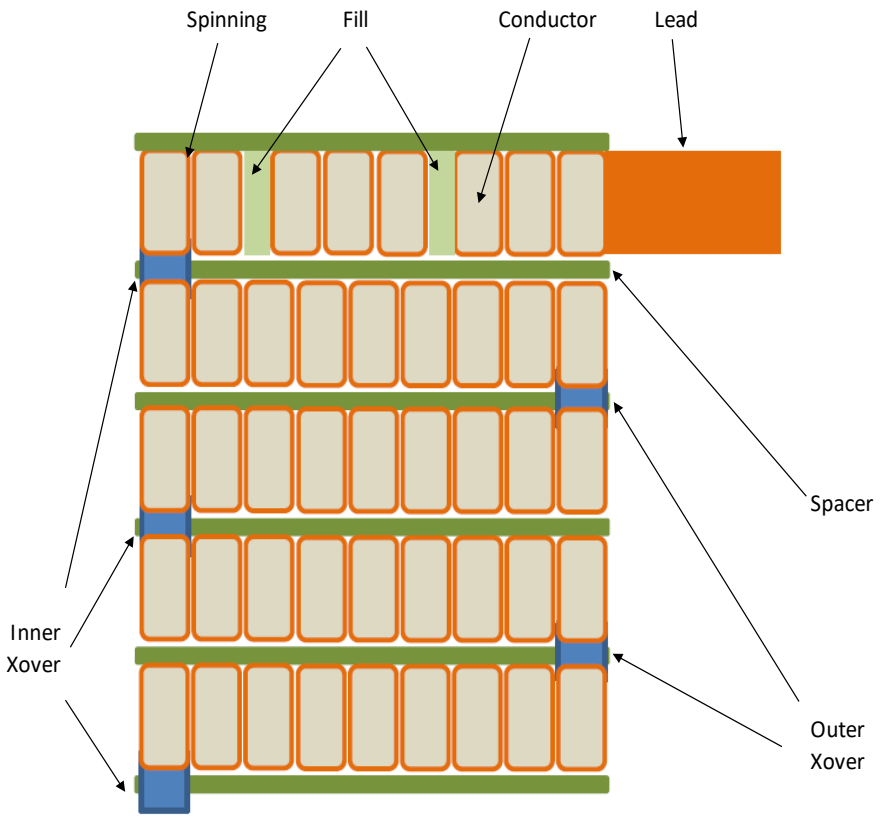
Insulation Materials

Minor Insulation

Insulation between different parts of one winding – between turns, stands 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



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Insulation Materials

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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

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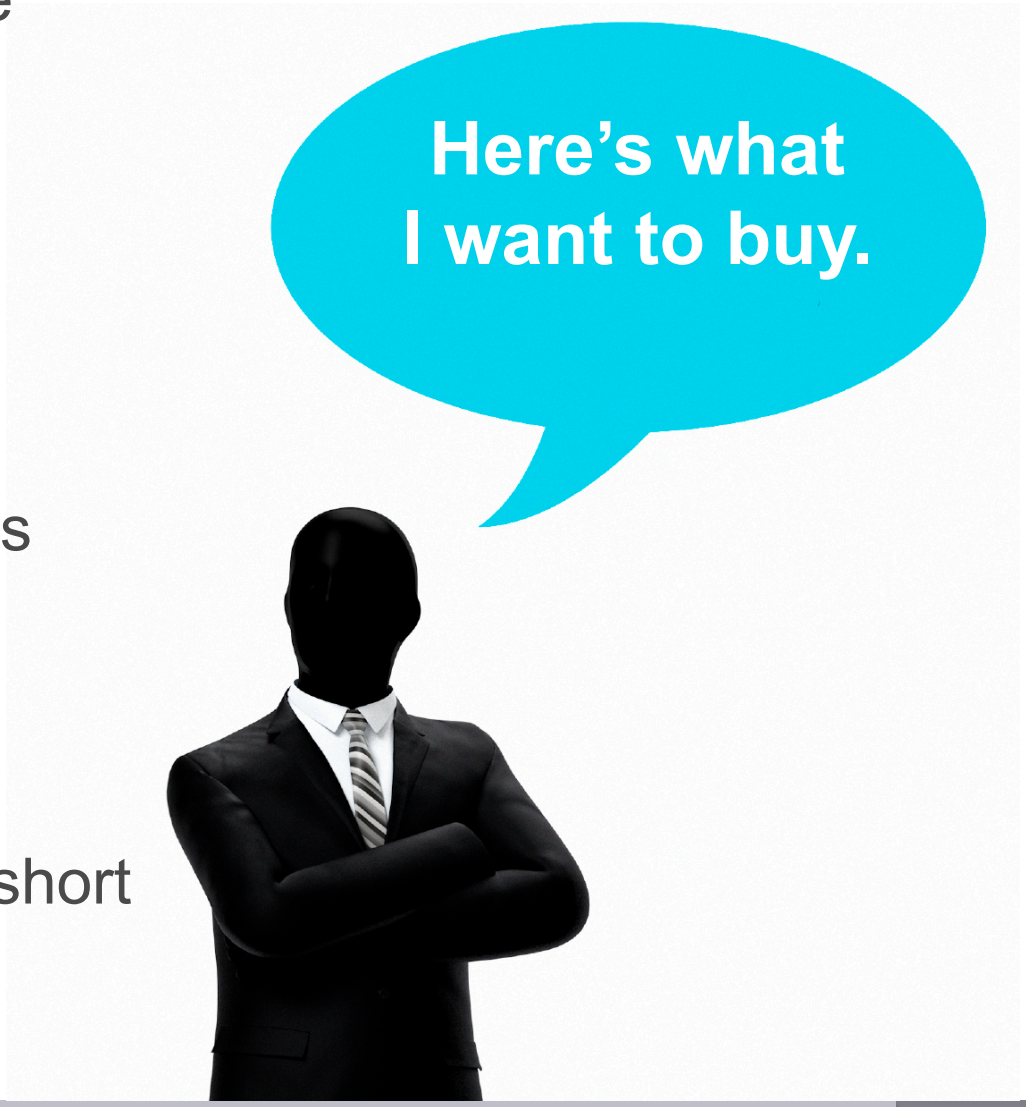
Requirements by Specification

- Type of core / Core Material
- Conductor Material Type
- Winding Type
- Sound Level
- Load Noise
- Special Loading
- Special %IZ
- Multiple Voltage Windings
- Stabilizing Windings
- Special Duty LTC
- GSU /Over fluxing
- Impact (High current for short duration) loading
- GIC



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Requirements by Specification

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Conductor Material

- Copper
- Aluminum
- Designer to Specify – Unless Critical

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Requirements by Specification

Winding Type

- Distribution Class Rectangular ≤ 2500 KVA
- Power Class Circular Disc ≥ 10,000 KVA
- Application Driven for In Between KVA

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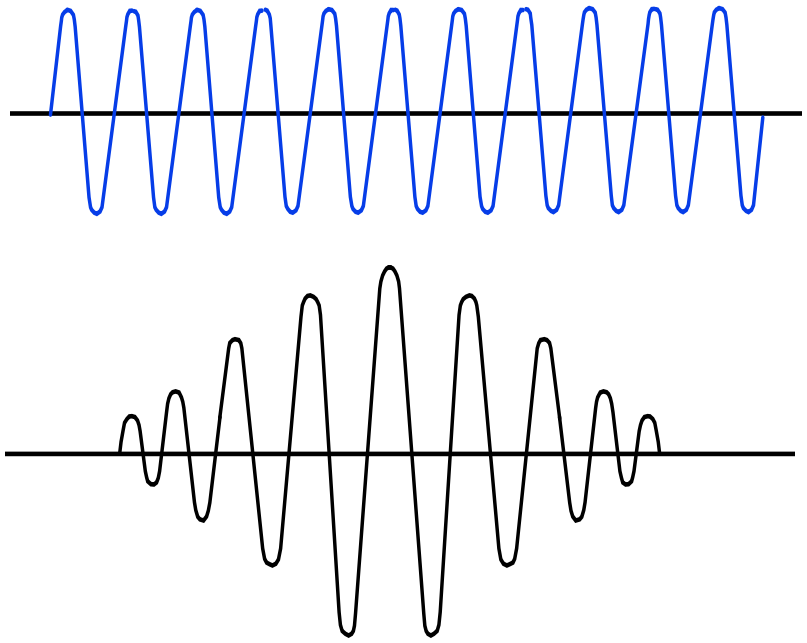
Requirements by Specification



Sound Level Requirements

- Standard per NEMA TRI
- $3/Watt or Higher
  No Load Evaluation *May*
  Achieve 5-10 db-A Lower
  (Flux Density)
- Additional Reduction for
  Increased Price
- Load Noise

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Requirements by Specification

Special Loading

- Summer/Winter Ambient Temperature Profiles
- Max Top Oil Temp
- Max Hot Spot Temp
- Max Loss of Life
- Higher Current Rating Components

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Requirements by Specification

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Special Loading

TO CONTROL	VARY THE DESIGN PARAMETER
Average oil temperature rise over ambient	Amount of coolers (radiators, fans, and pumps) and Thermal time constant of the unit
Winding gradient	Current densities in winding conductors and cooling surface within the winding
Hot spot gradient	Current densities in winding conductors and distribution of stray losses

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Requirements by Specification

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Special Loading

Harmonics

- Higher than Normal (<0.05 per unit)
- User must specify entire harmonic profile
- Affects temperature rise, eddy and stray losses
- Larger “equivalent” KVA

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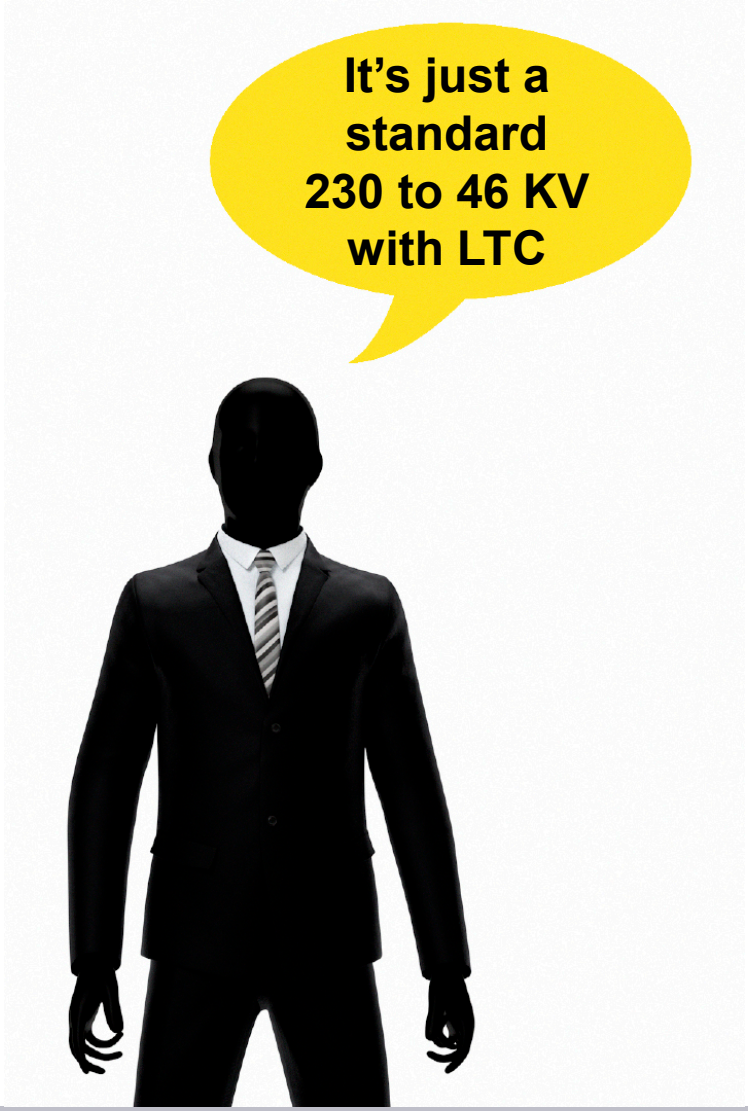
Requirements by Specification



Impedance

Standard % IZ

- Most Economical Design
- BIL and LTC Dependent
- HV-LV Winding Clearance
- LTC Leads

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Requirements by Specification

Impedance

Tertiary % IZ vs. Fault Current

- May lead to less economical design

Special % IZ

- Lower Impedance
  - Minimize Regulation
  - Match existing unit
  - Causes higher short circuit currents
  - Increases cost - more strength needed

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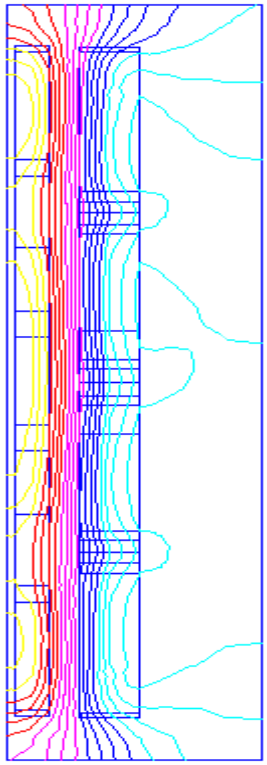
Requirements by Specification

Impedance

Special % IZ

- **Higher Impedance**
  - Limits fault current
  - Higher regulation for poor power factor
  - Higher stray losses
  - Possible over-heating due to leakage flux related stray losses, can raise price of unit



Leakage flux stray losses

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Requirements by Specification

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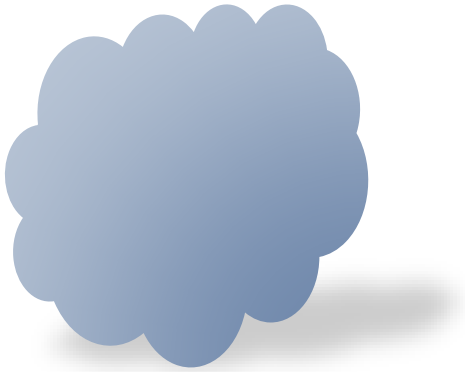
Multiple Voltage Windings

- Future system upgrades
- System spare for different voltages
- Even multiple - cost effective design
- Uneven multiple - can cause problems

Even =

Uneven =



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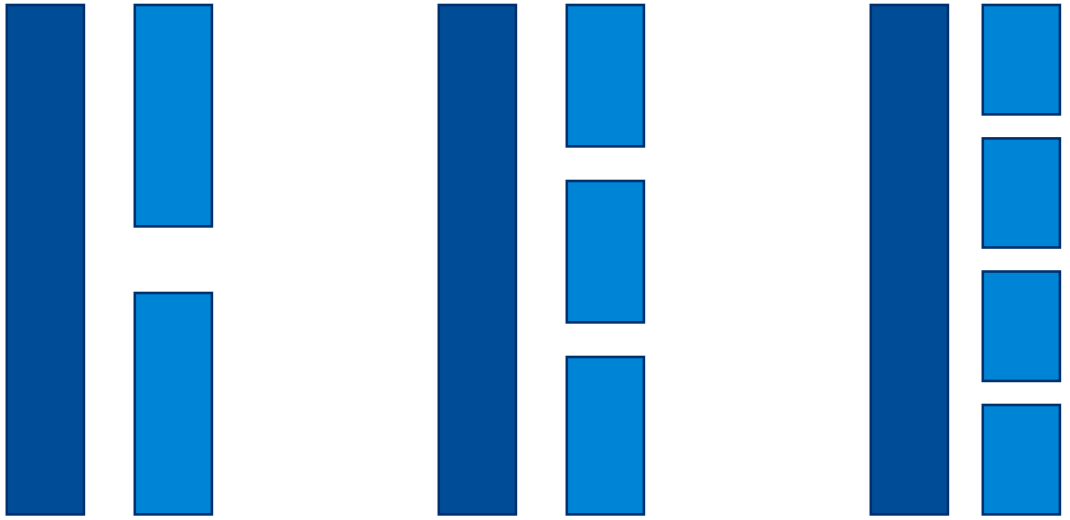
Multiple Voltage Windings

- Evens Ratio, Good Ampere-Turn Balance
- Minimum Short-Circuit Forces
- Minimum Stray Loss Problems



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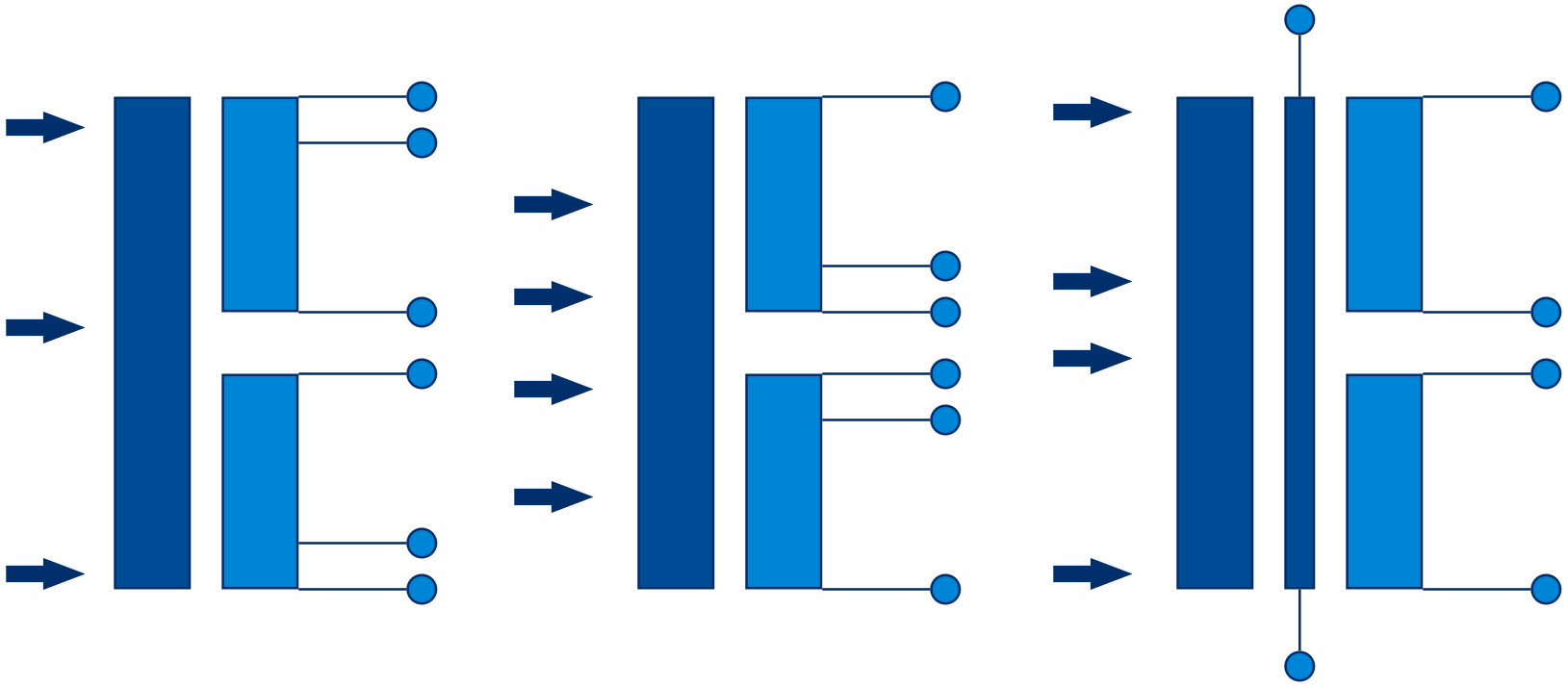
Multiple Voltage Windings

- Uneven Ratio, Bad Ampere-Turn Balance
- Large Short-Circuit Forces
- Potential Stray Loss Problems



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Requirements by Specification

Multiple Voltage Windings

Uneven Multiple Concerns

- Short circuit forces
- Stray losses
- Winding stresses
- Complicated switches or terminal boards
- Specify when economically justified

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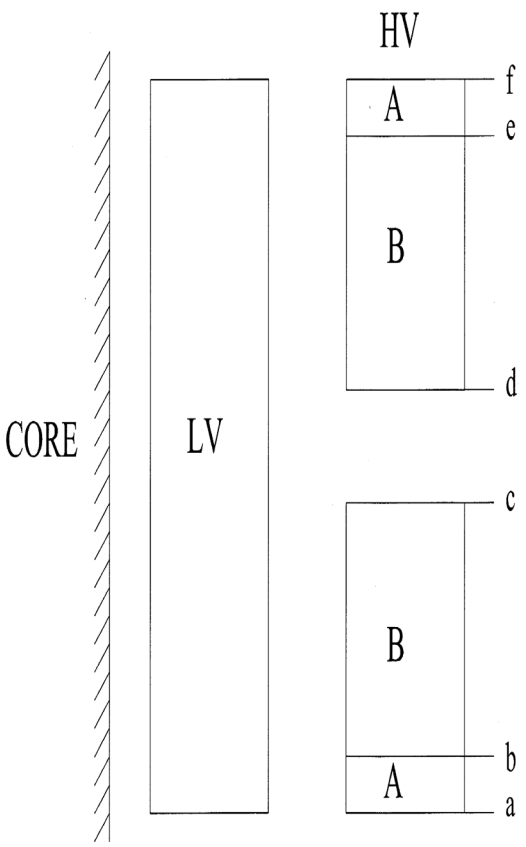
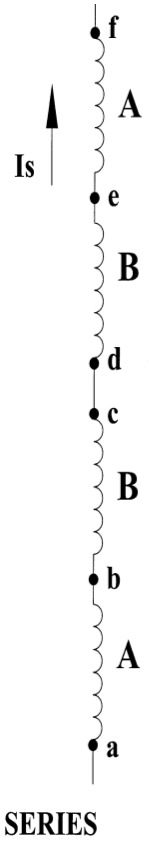
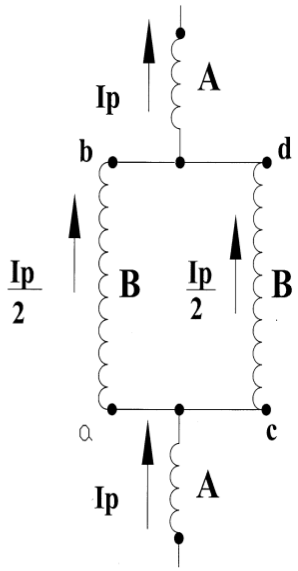
Requirements by Specification

Multiple Voltage Windings

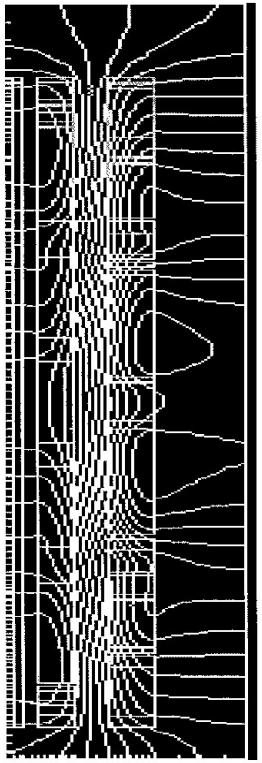




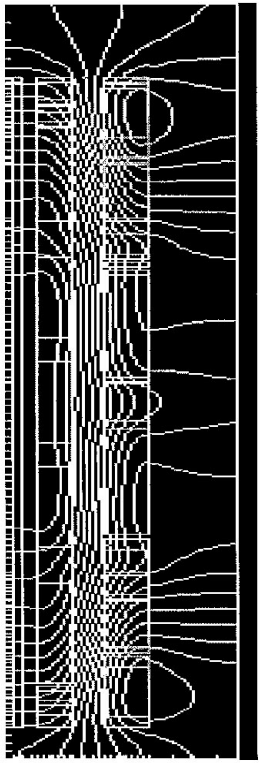
SERIES



PARALLEL



Series



Parallel

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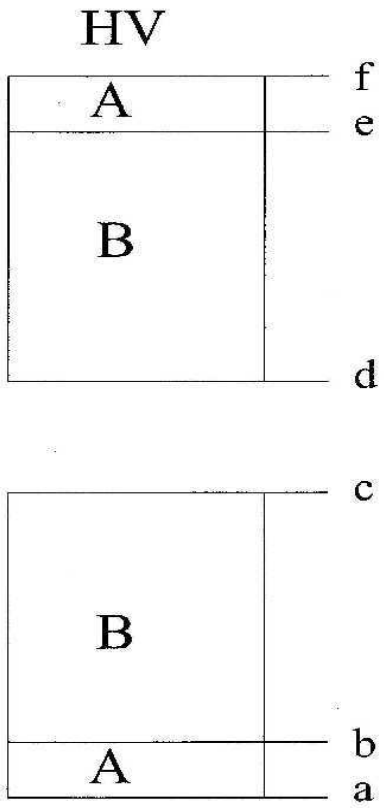
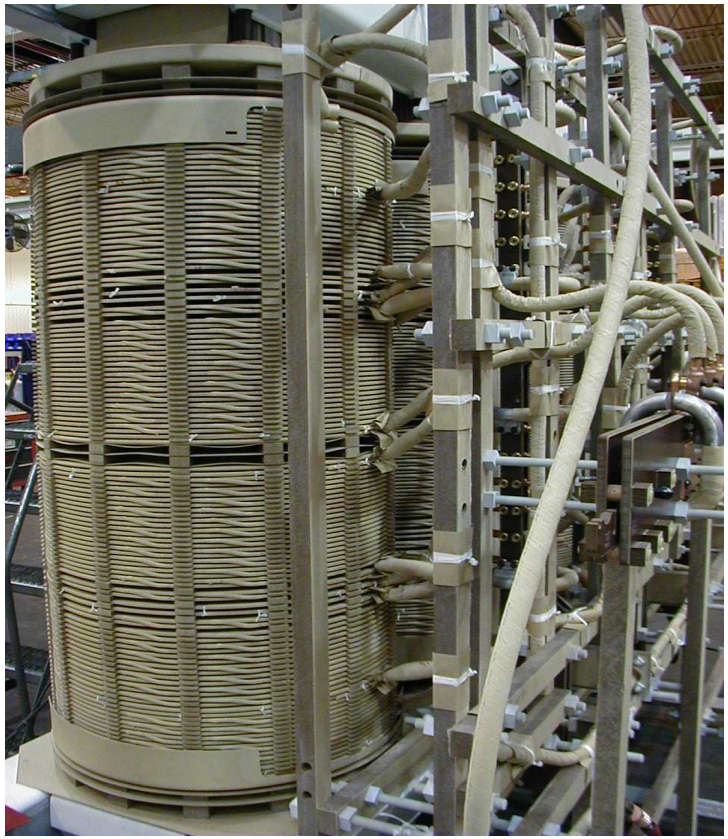
Requirements by Specification

Multiple Voltage Windings





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Requirements by Specification

Stabilizing Winding

- Delta connected in Y-Y transformers and Y-connected auto's
- Long term practice
- Taken for granted as necessary
- Defined in ANSI C.57.80

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Requirements by Specification

SPX

WAUKESHA

Stabilizing Winding

As Defined in IEEE/ANSI C57.12.80

- To stabilize the neutral point of the fundamental frequency voltages
- To minimize third-harmonic voltage and the resultant effects on the system
- To mitigate telephone influence due to third-harmonic currents and voltages
- To minimize the residual direct-current magnetomotive force on the core
- To decrease the zero-sequence impedance of transformers with Y-connected windings

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Requirements by Specification

SPX

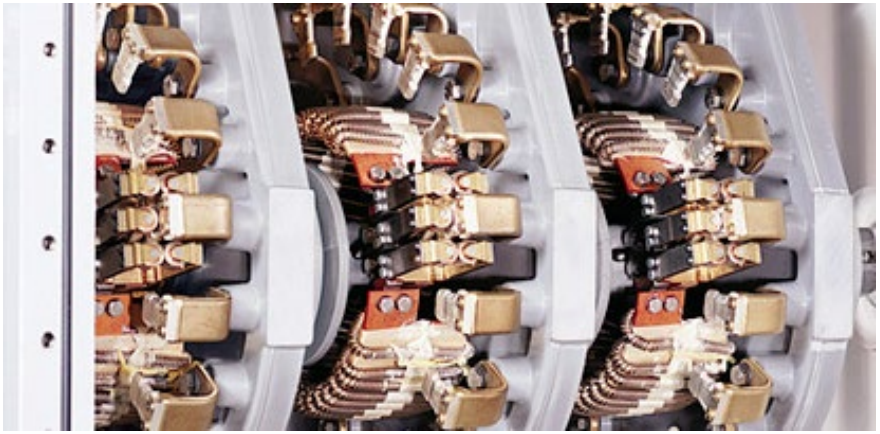
WAUKESHA

Stabilizing Winding

Per B.A. Cogbill paper "Are Stabilizing Windings Necessary in all Y-Connected Transformers?" (1959)

- Not needed in many cases when 3-legged cores are used
- Questionable need with other core design

Requirements by Specification



Special Duty LTC

"Initiate and complete tap changes during short circuit faults"

- Increases LTC current rating requirement
- Large series transformer
- Extremely low probability

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GSU

- Good reference C57.116 Guide
- Wye – Delta for UT
- Delta-Wye for UAT and SST
- Over excitation
- Voltage Regulation considerations
- Breaker Protection

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GIC Flow

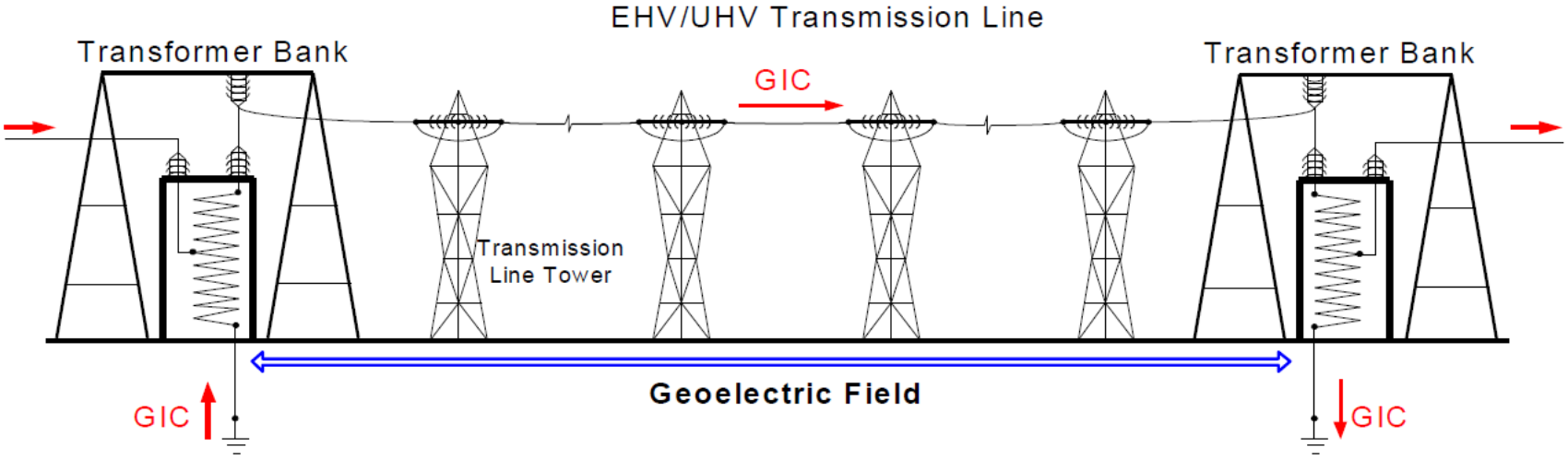

Figure 1—GIC flow in a power network

Factors Influencing the Degree of Risk to the Grid and Equipment:

- Geomagnetic Latitude
- Local Earth Resistivity
- Coastal Effect
- Network Topology
- Design and Specification of Key Equipment
- Storm Duration
- Loading

C57.163-2015 – GIC Guide

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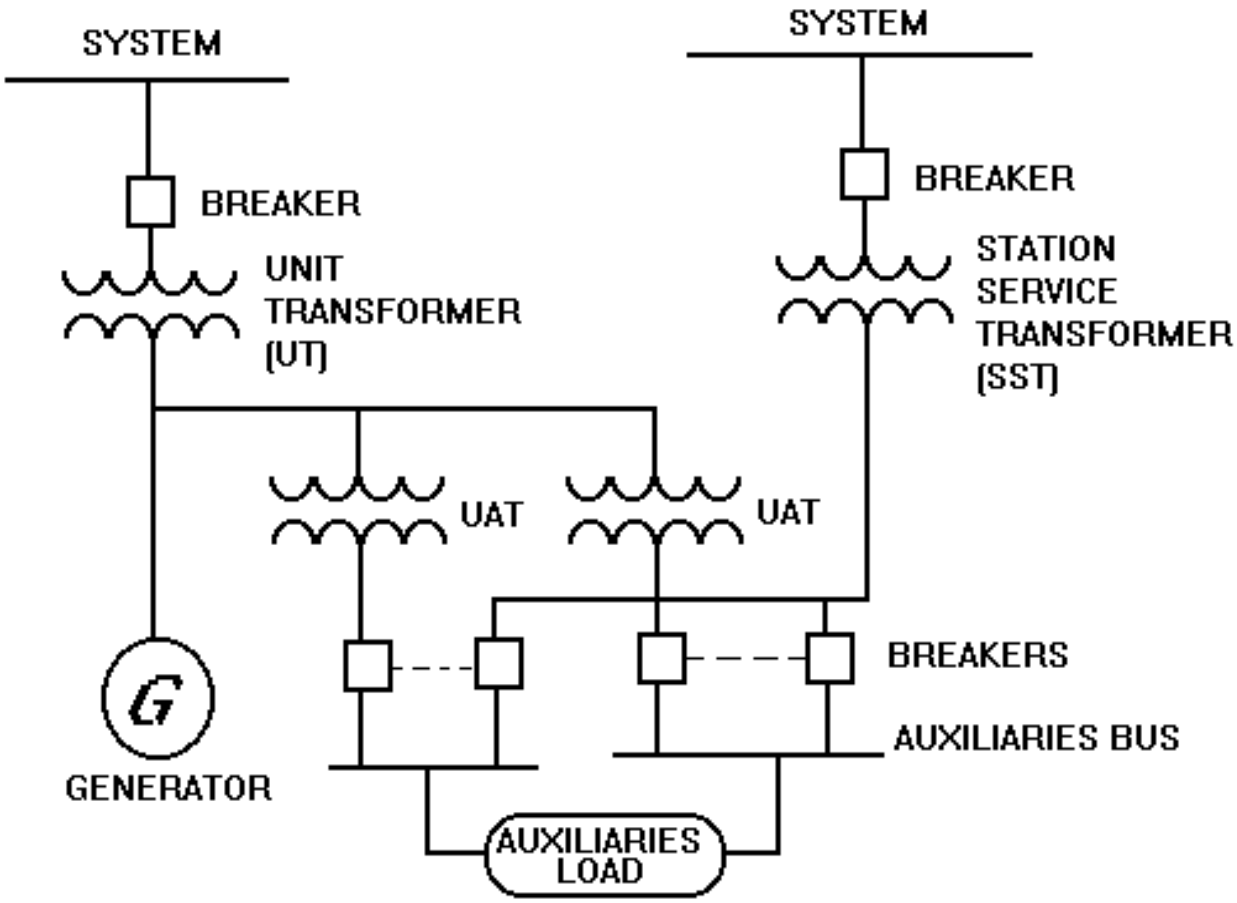
Power System One-Line Diagram



Typical Generating Station Auxiliaries Power System One-Line Diagram

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Impact Loading

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- Mechanical and Thermal Performance Considerations
- Full Voltage Start
- Reduced Voltage Start
- How many starts per hour?
- “Bumpless Transmission” with Variable Frequency Drives

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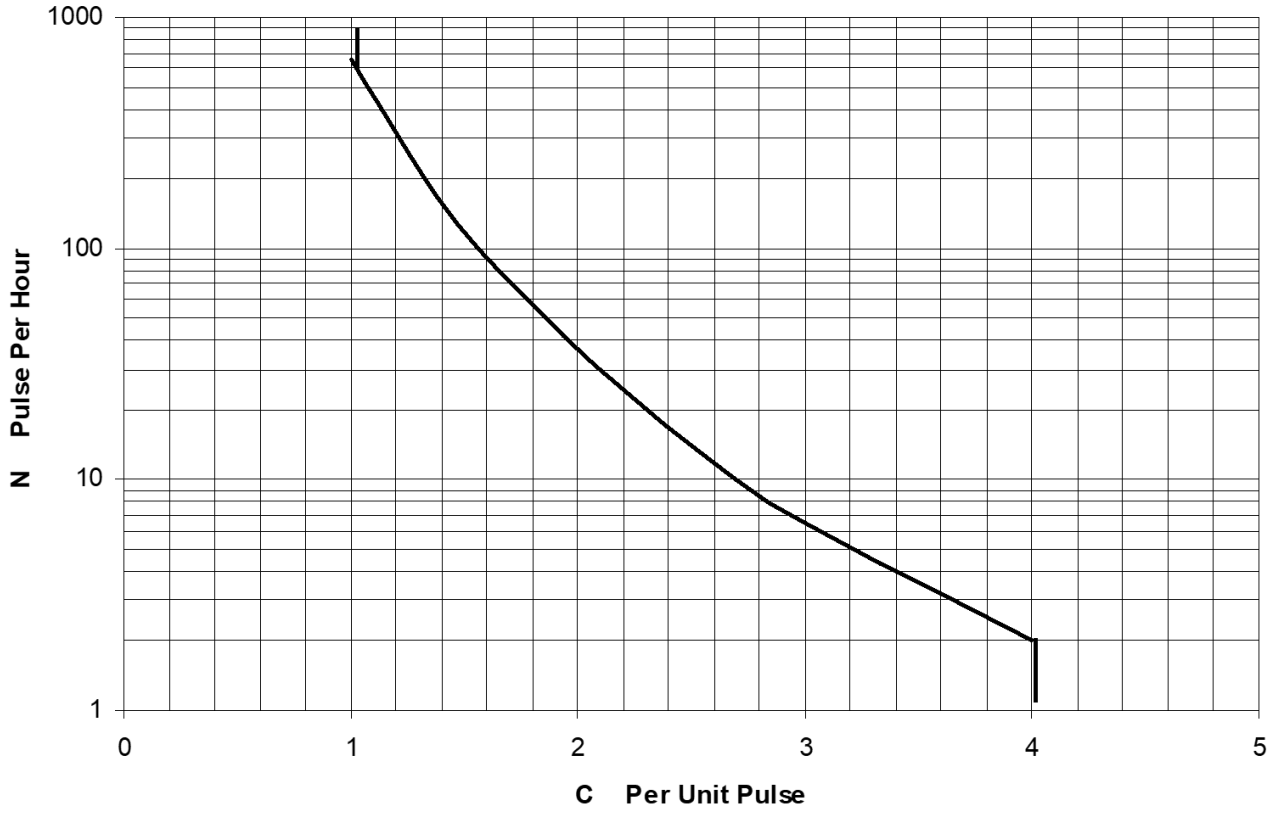
Impact Loading (high current for short duration)

Transformer MVA > Full Load MVA
Transformer MVA > RMS MVA or Combined Starting and Load Cycle
Transformer MVA > Starting MVA / C



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Test Requirements

SPX

WAUKESHA

ANSI/IEEE Requirements

- Routine - All Units
- Design - Manufacturer Determines
- Other - User Specified

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Test Requirements

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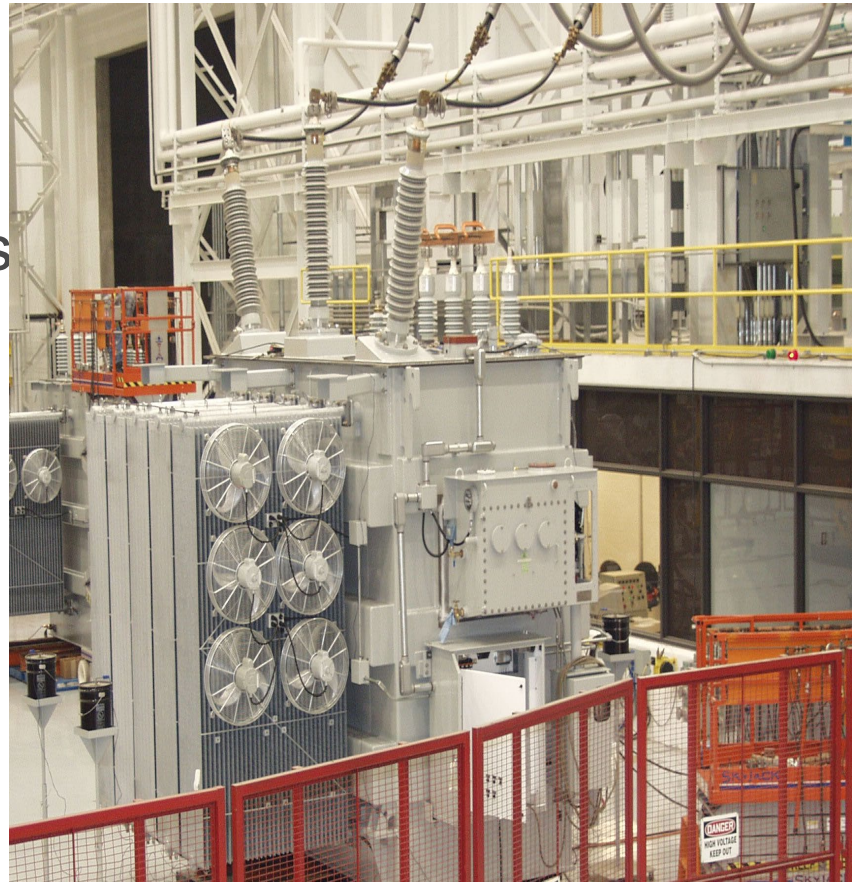
- **Temperature Rise Test**
- Time / energy consuming
- Occupies test floor and disrupts normal production cycle
- User specific non-standard
- M and N , C57-119
- Use of Fiber optics
- Low DGA
- **No load 24 Hours**
- **Resistance -all taps**
- **Doble 10 kv –all taps**



Others

- Documentation
- Bushing Current Transformers
- Odds and Ends????

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Others

Documentation

- **Lots of formats**
  - CAD files
  - Mylar
  - Aperture Cards
  - Volumes of Prints
- **Reduce Costs – Order only format and quantity needed**

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Others

Current Transformers

- **Be aware of size**
  - Low ratio, high relay burden means *BIG* and heavy
  - Problems in small units
- **Minimize CT accuracy class when possible**

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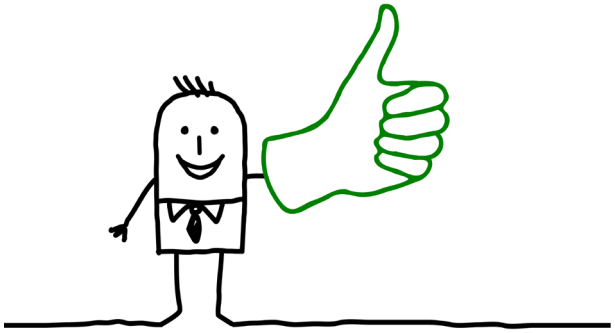
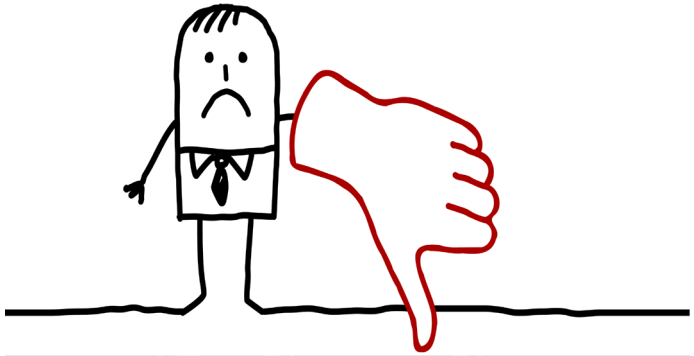
Others

Odds and Ends (Add Cost, Small Value)

- No Brazed Joints
- Maximum Fan Speed
- Gasket versus O-Ring
- 3-Phase Auxiliary Power
- LTC in Segment 1 or 3
- Large No. Fiber Optics
- Very Low DGA
- Very Low PD
- Busbar for Ground Conductor
- Minimum Print Text Size
- Minimum Control Wire Size
- Tap Switch above Coils





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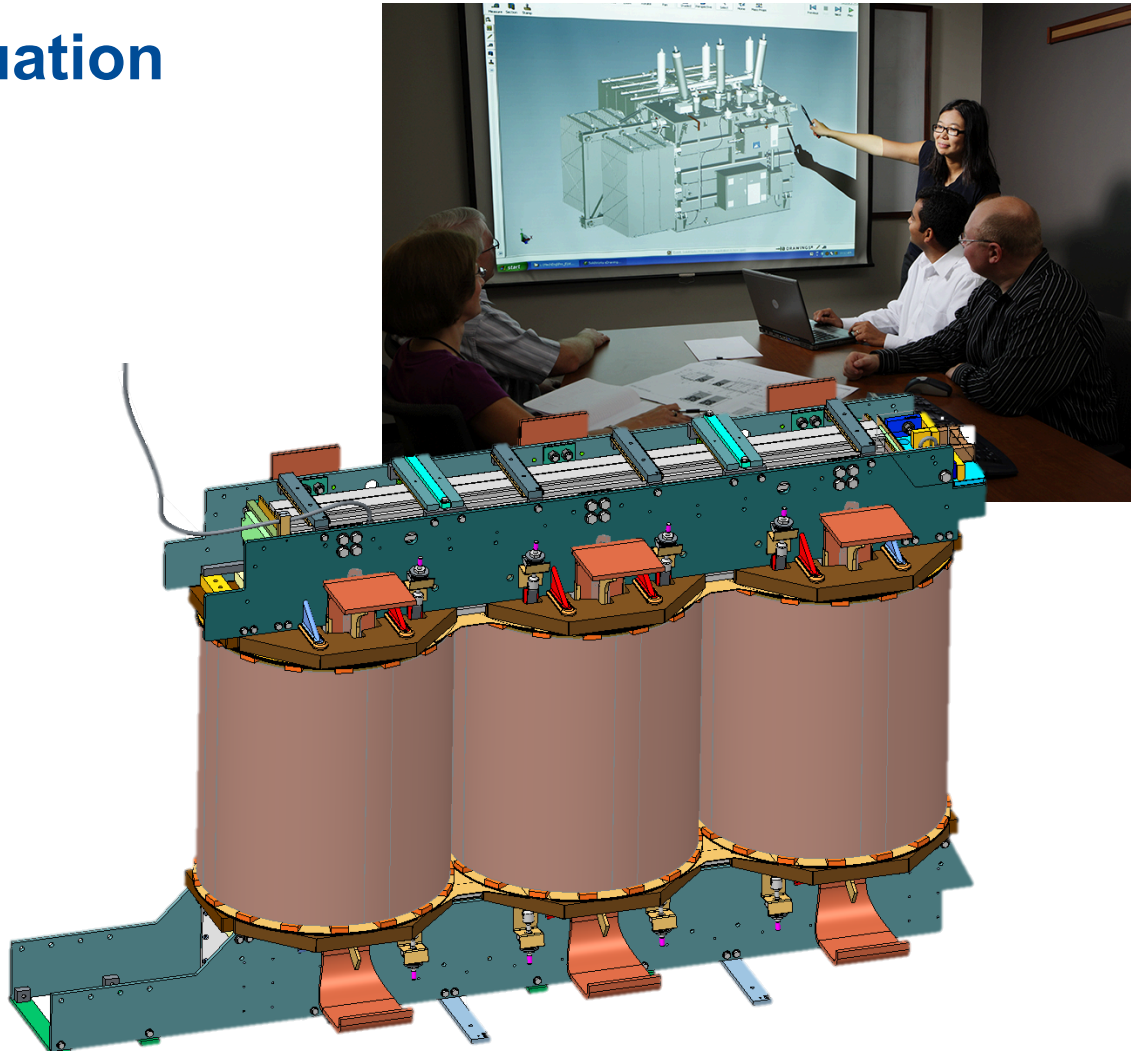
Transformer Design Parameters

High Load Loss Evaluation

- Larger Core Diameter
- Fewer Turns
- Squatty Windings
- Larger Magnet Wire
- Lower Current Density
- Higher Flux Density



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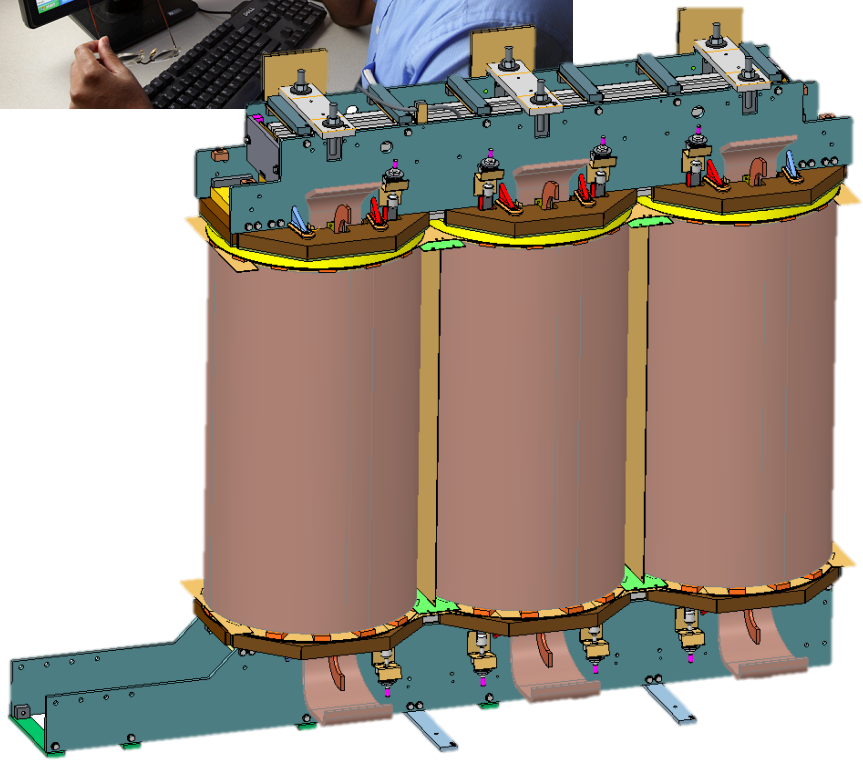
Transformer Design Parameters



High No-Load Loss Evaluation / Low Sound

- Smaller core diameters
- More Turns
- Tall, thin windings
- Smaller magnet wire
- Higher current density
- Lower flux density

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Transformer Design Parameters

Lightest Weight, No Loss Evaluation

- Small core diameter
- Fewer turns
- Tall skinny windings
- Small magnet wire
- higher current density
- higher flux density
- Higher losses, more cooling
- Higher noise

“I want the lowest price!! OKAY?!”

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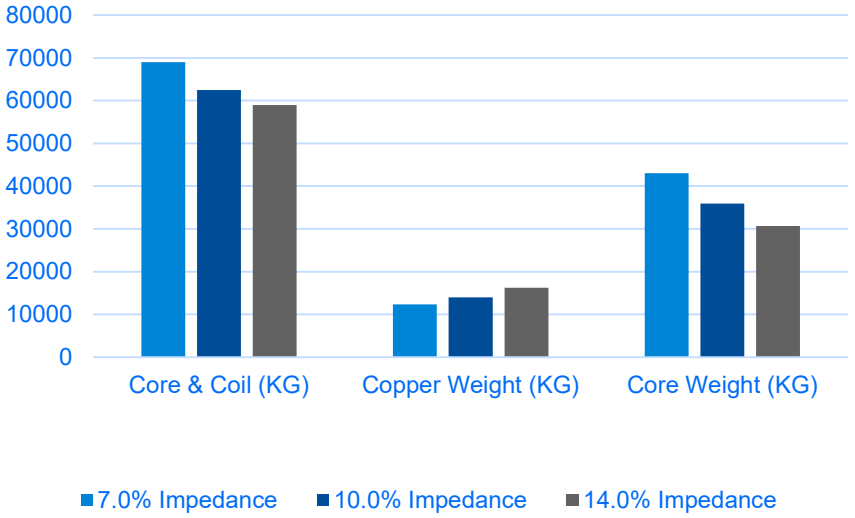
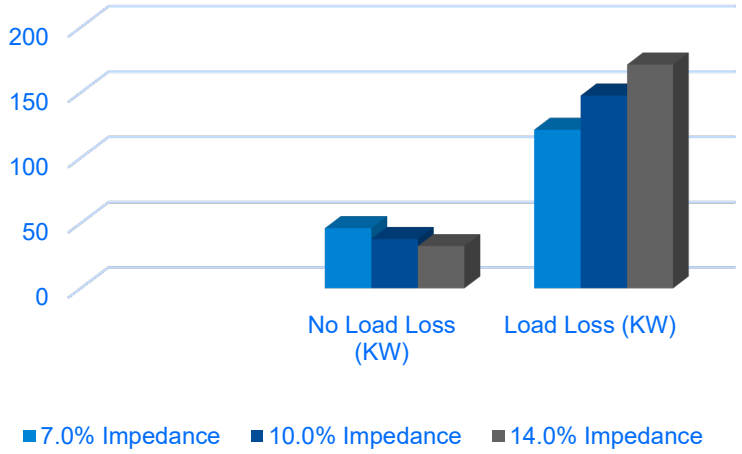
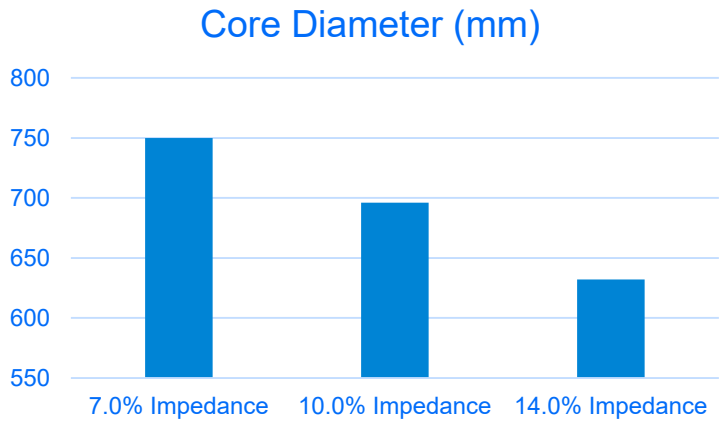
Impact of Change In Impedance





Impedance (%)	7.0	10.0	14.0
Capacity (MVA)	60/80/100/112	60/80/100/112	60/80/100/112
HV KV	230	230	230
LV KV	34.5	34.5	34.5
Vector Group	Dyn1	Dyn1	Dyn1



Transformer Design Parameters

Optimum Design – *A Balance*

- Cost of variable items
  - oil, conductor, steel
- Cost of constant items
  - bushings, gages, CT's
- Cost of losses
- Cost of manufacturing
- ***Customer Satisfaction***

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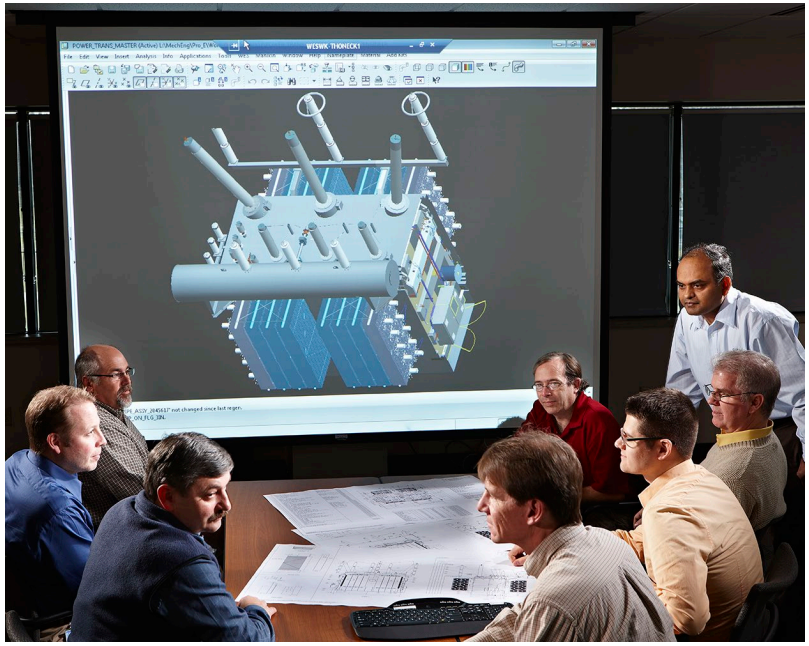
Optimization of a Design

- Determine the ranges of the major characteristics
- Basic transformer requirements (voltage, KVA, impedance, temperature rises and sound level)
- Computer programs
- Best transformer design the application



Questions?

Thank you!

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