Transformers: A Sample Design and Basic Principles

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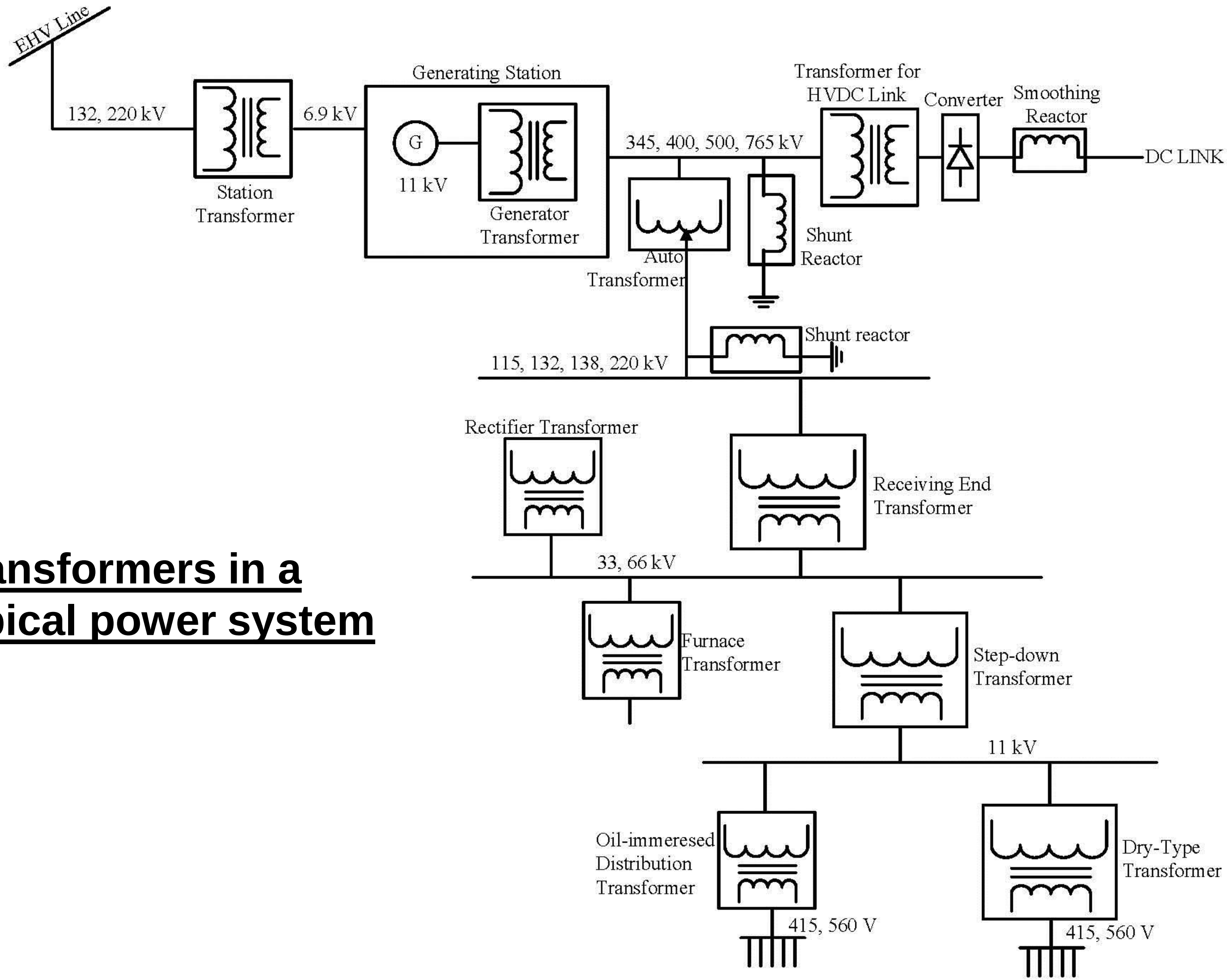


Transformers in a typical power system

Design of a 31.5 MVA, 132/33 Power Transformer

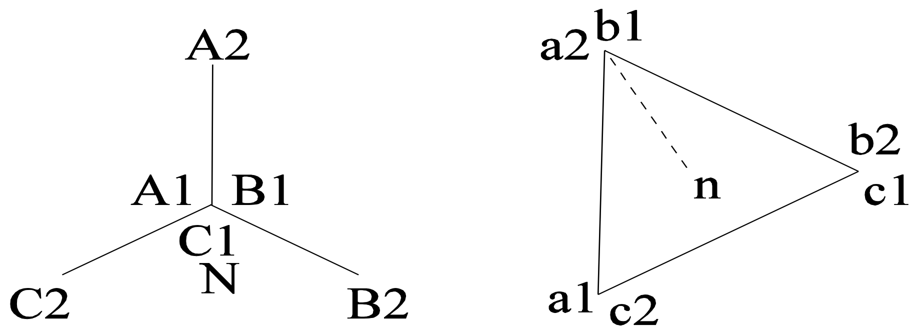
Specification

Rating	**: 3-phase, 31.5 MVA, 132/33 kV**
Vector group	**: Yd1**
Frequency	**: 50 Hz**
No-load loss	**: 26 kW**
Load loss	**: 146 kW**

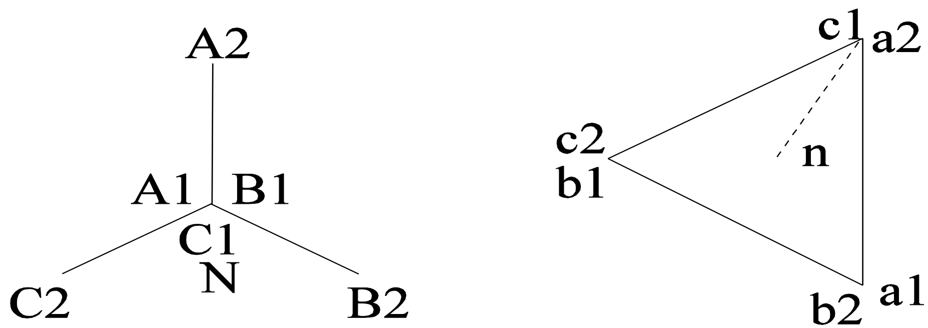
Source of the design: S. V. Kulkarni, and S. A. Khaparde, *Transformer Engineering: Design, Technology, and Diagnostics*, Second Edition, CRC Press, Taylor & Francis Group, September 2012.

Vector Groups

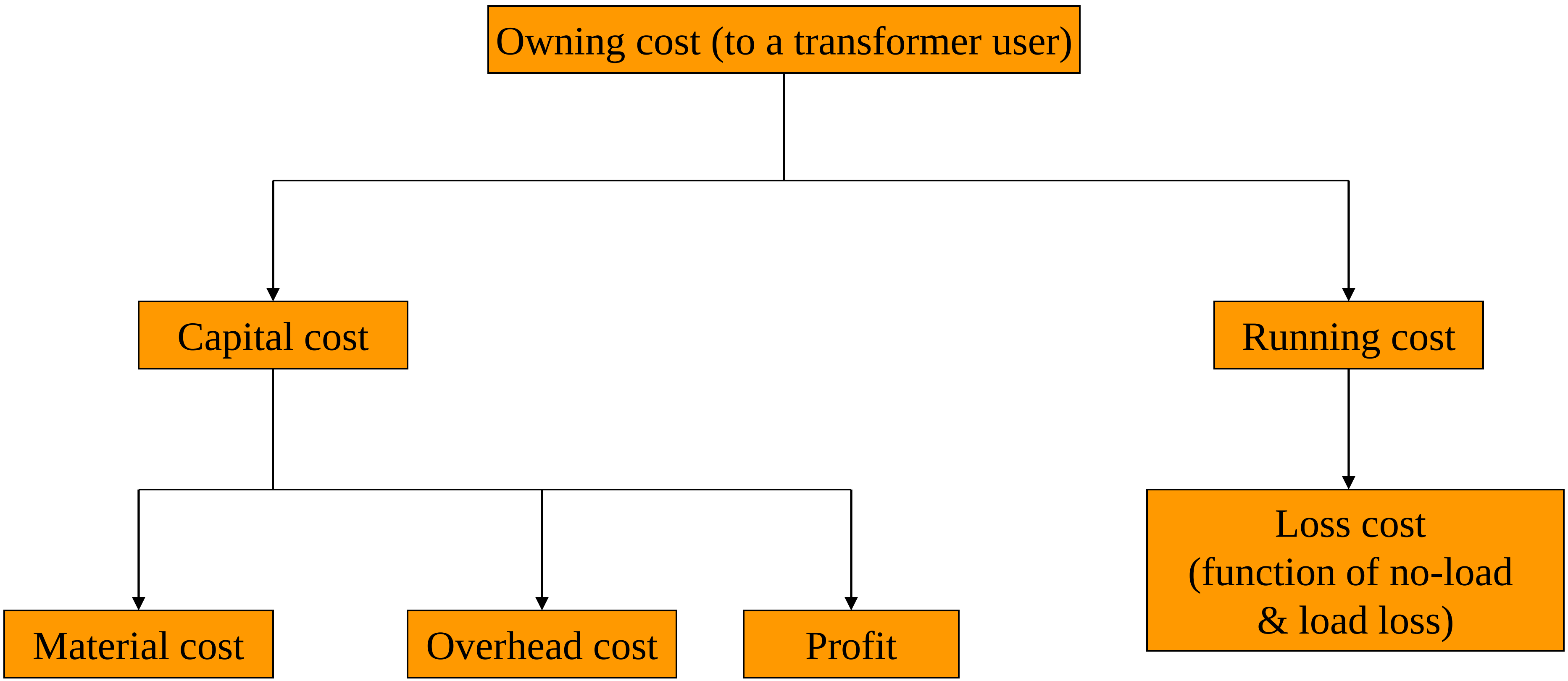
Yd11



Yd1



Total owning cost of a transformer



Note: Higher the material cost (& the capital cost) lower is the running cost.

Therefore, the owning cost needs to be optimized.

Core Design

- Selection of core diameter – based on experience or some empirical formula. Let us select it as 54 cm.
- Core area with 0.9 as space factor

$$=0.9*((\prod /4)* 54^2) = 2290*0.9= 2061 \text{ cm}^2$$

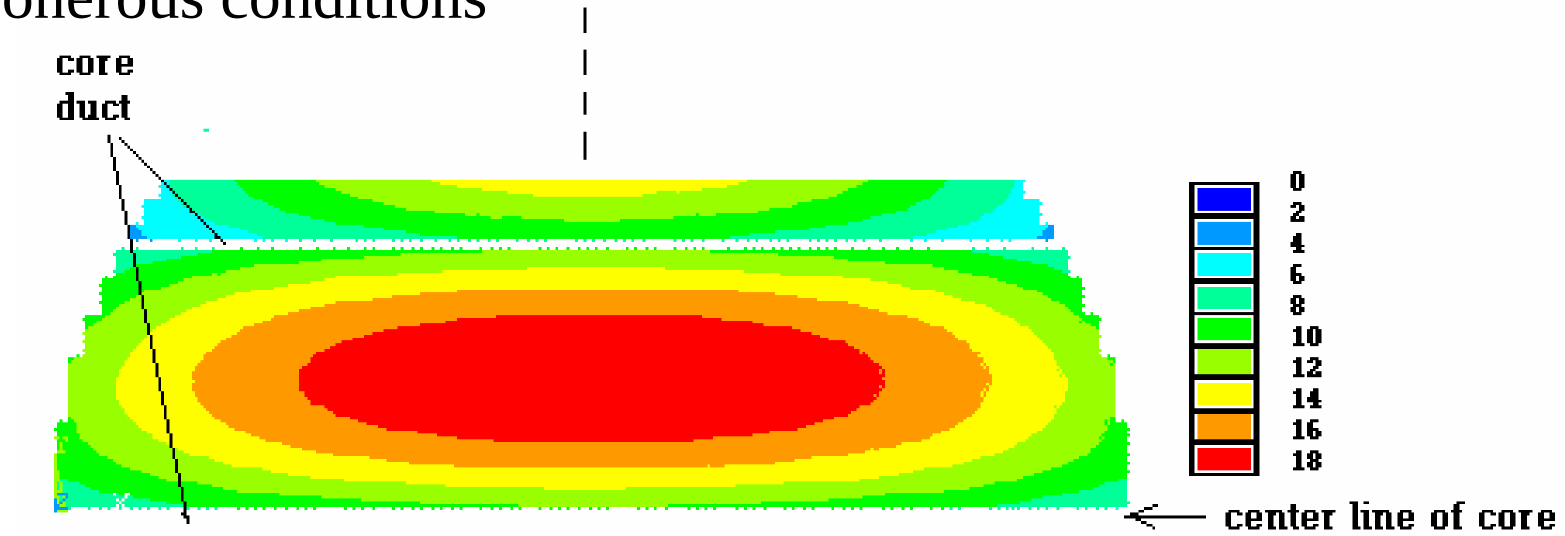
- Maximum flux density that can be used for CRGO material is 1.73 tesla (knee point: 1.9 Tesla, saturation: 2.03 Tesla)
- Let us choose B_m=1.7 Tesla
- Emf equation for transformer is

$$V= 4.44*\phi *f* T = 4.44*(B_m*A_c)*50*T$$

$$=> V/T = 4.44*1.7*0.2061*50=77.78$$

Core Temperature Rise

- Design of optimum number of cooling ducts
- Requires determination of temperature profile under most onerous conditions



- For most accurate temperature rise estimation, 3-D FEM analysis required with consideration of anisotropic thermal properties
- The limits of temperature rise for core surface and interior portions are generally different

LV Design

- First choose the number of LV turns,

  LV voltage= 33 kV

  (it is a delta connected winding, line voltage = phase voltage)

  LV turns = 33000/77.78 = 424.3 ≈ 424 turns

- Recalculate flux density as B_m=1.701 tesla,

  V/T=33000/424 = 77.83

- Current (phase) = 31500/(3*33) = 318.2 A
- Insulation level: 70 kVrms/170 kVp
- Choose number of discs = 106,

  4 turns/disc: 106*4=424 turns

INSULATION LEVEL

- High voltage equipments need to withstand overvoltages (much higher than their rated voltage): i) switching overvoltages

  ii) lightning overvoltages
- Protective devices are used (e.g. lightning arresters).
- Insulation coordination is done between the insulation level (breakdown voltage) of the protective devices and that of the HV equipments

  A protective device is typically designed to operate at 80% of the HV equipment insulation level.
- Insulation levels are standardized.

Transformers

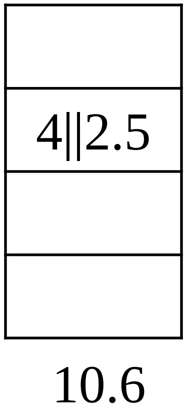
Rated Voltage	1 minute power frequency over-voltage test	1.2/50 μsec lightning test over-voltage
11 kV	28 kV_{rms}	75 kV_P
33 kV	70 kV_{rms}	170 kV_P
132 kV	230 kV_{rms}	550 kV_P
220 kV	395 kV_{rms}	950 kV_P

- Higher the over-voltage level, lower is the time of application of test voltage.

- Choose current density of 3 A/mm^2
- Cross sectional area of LV conductor

  = 318.2/3= 106 mm^2

- Area=10.6*2.5*4 = 106 mm^2



- Insulation on conductors: 0.7 mm,
- Insulation between discs = 3.0 mm
- Height of the winding

  = (10.6+0.7+3.0)*106 – 3.0 = 1513 ≈1520 mm

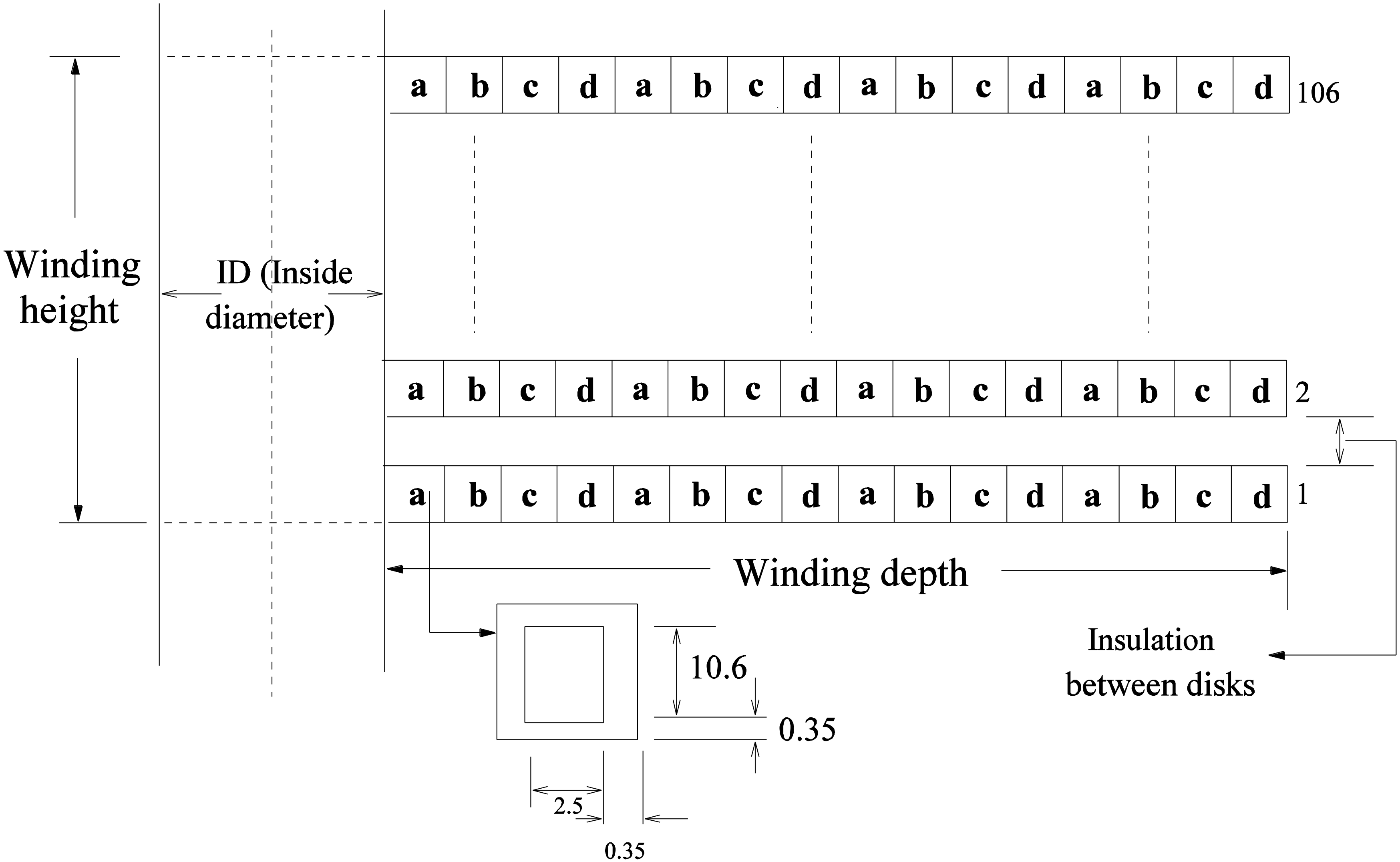
- Depth of the winding

  = [(2.5+0.7)*4]*4

  =51.2 mm ≈ 52 mm

Note: Design parameters are not optimum; values are chosen for convenience while explaining the design

LV Winding


a b c d a b c d a b c d a b c d
106
Winding height
ID (Inside diameter)
2
1
Winding depth
10.6
0.35
2.5
0.35
Insulation between disks

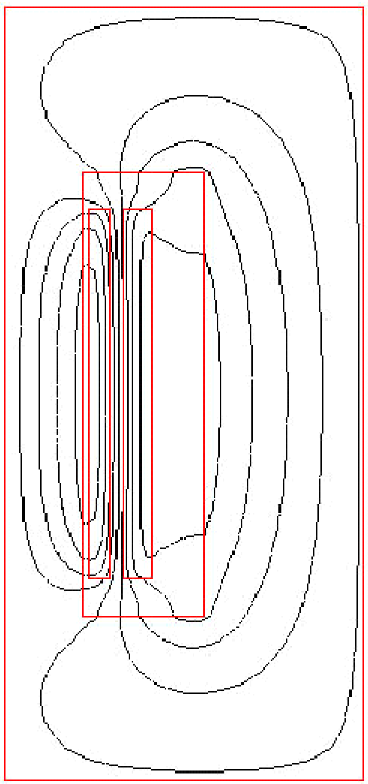
Windings

- Design of windings is influenced by the following considerations
  - electromagnetic (eddy / stray losses)
  - dielectric
  - short circuit
  - thermal
- These design considerations have often conflicting requirements:
  - conductor radius : dielectric Vs short circuit
  - paper covering : dielectric Vs thermal
  - conductor thickness : short circuit Vs eddy loss
  - first duct : thermal Vs dielectric
  - radial spacer width : thermal Vs short circuit
- Judicious selection of design parameters is necessary

Eddy Loss Evaluation and Optimization

- Eddy loss per unit volume for a thin conductor

$$P_E = \frac{\omega^2 B^2 t^2}{24\rho}$$



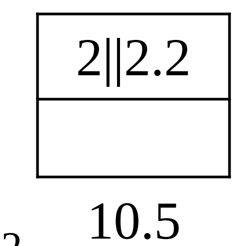
- where,
  - ω is frequency in rad/sec
  - B is the peak value of tangential leakage flux density on the conductor surface (B_y or B_x)
  - t is the dimension of the conductor perpendicular to field (conductor *thickness* or *width*)
  - ρ is the resistivity of the conductor material

HV Design:

- Current (phase) = 31500/(132*√3) = 137.78 A
- Insulation level: 230 kVrms / 550 kVp impulse
- HV turns = (132000/√3)/77.83 = 979.2 ≈ 980 turns
- Choose 98 D, 10T/D; 98*10 = 980 turns
- Conductor covering = 1 mm, insulation between discs = 4 mm
- Conductor width = 1520/98 – 1 – 4 ≡ 10.5 mm
- For conductor density of 3 A/mm^2, total conductor area required= 137.78/3 = 45.9 mm^2
- Hence, choose two parallel conductors as:

  Area of turn = 46.2 mm^2

  => current density = 2.98 A/mm^2



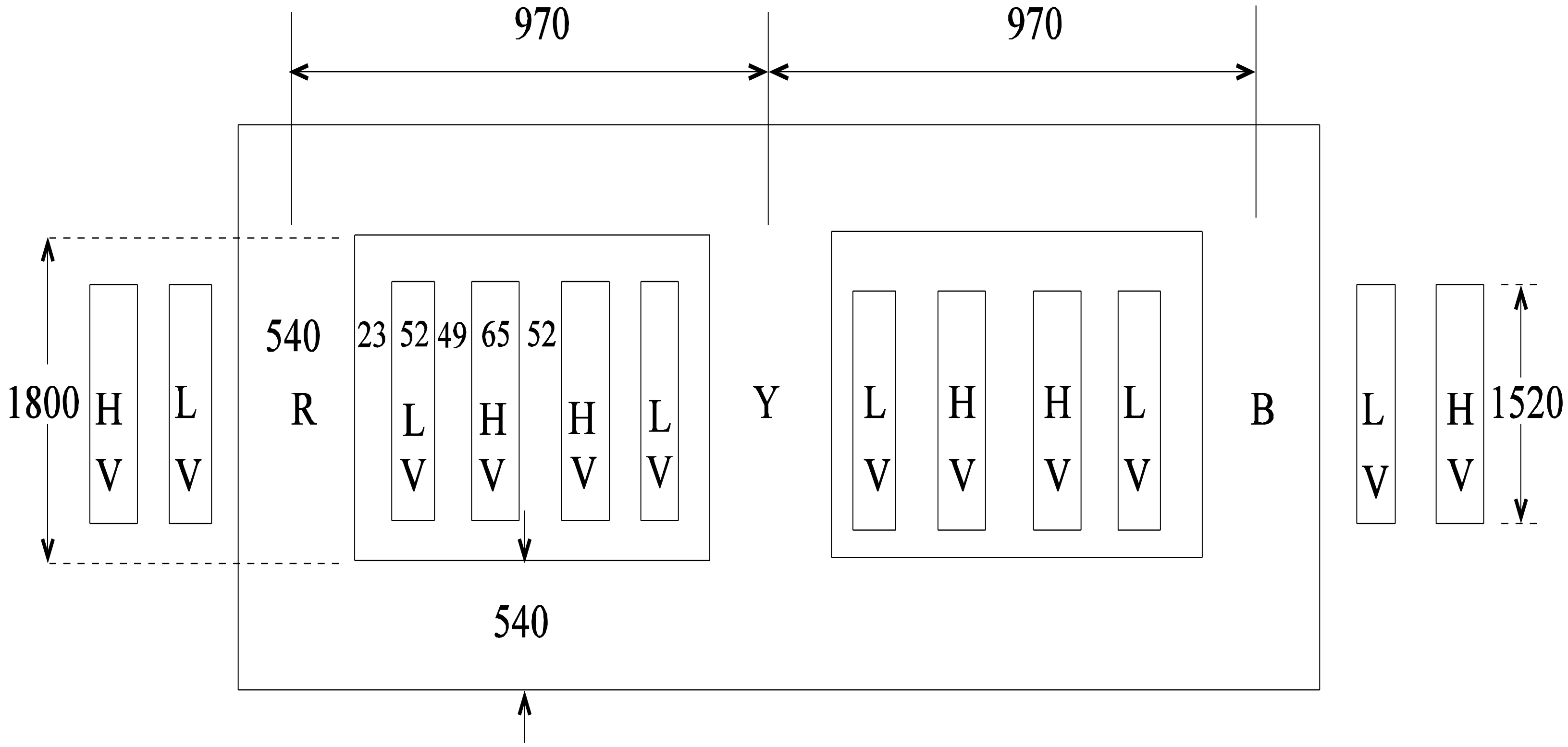
- HV radial depth = [(2.2+1)*2]*10 +1 (tolerance)= 65 mm

Note: Design parameters are not optimum; values are chosen for convenience while explaining the design

Design Continued….

Core diameter		540 mm
Core-LV	:23	563 mm (mean diameter)
		586 mm (LV-ID)
LV	:52	638 mm (LV mean diameter)
		690 mm (LV-OD)
LV-HV gap	:49	739 mm (mean diameter)
		788 mm (HV-ID)
HV	:65	853 mm (HV mean diameter)
		918 mm (HV-OD)
Phase-Phase	:52	

Note: Design parameters are not optimum; values are chosen for convenience while explaining the design


970
970
1800
H V
L V
540
R
23
52
49
65
52
L V
H V
H V
L V
Y
L V
H V
H V
L V
B
L V
H V
1520
540

- Center to center distance =970 mm
- Winding to top yoke clearance= 200 mm and winding to bottom yoke clearance = 80 mm
- Window height = winding height + 200 + 80 = 1520+280= 1800 mm
- Mean length of core

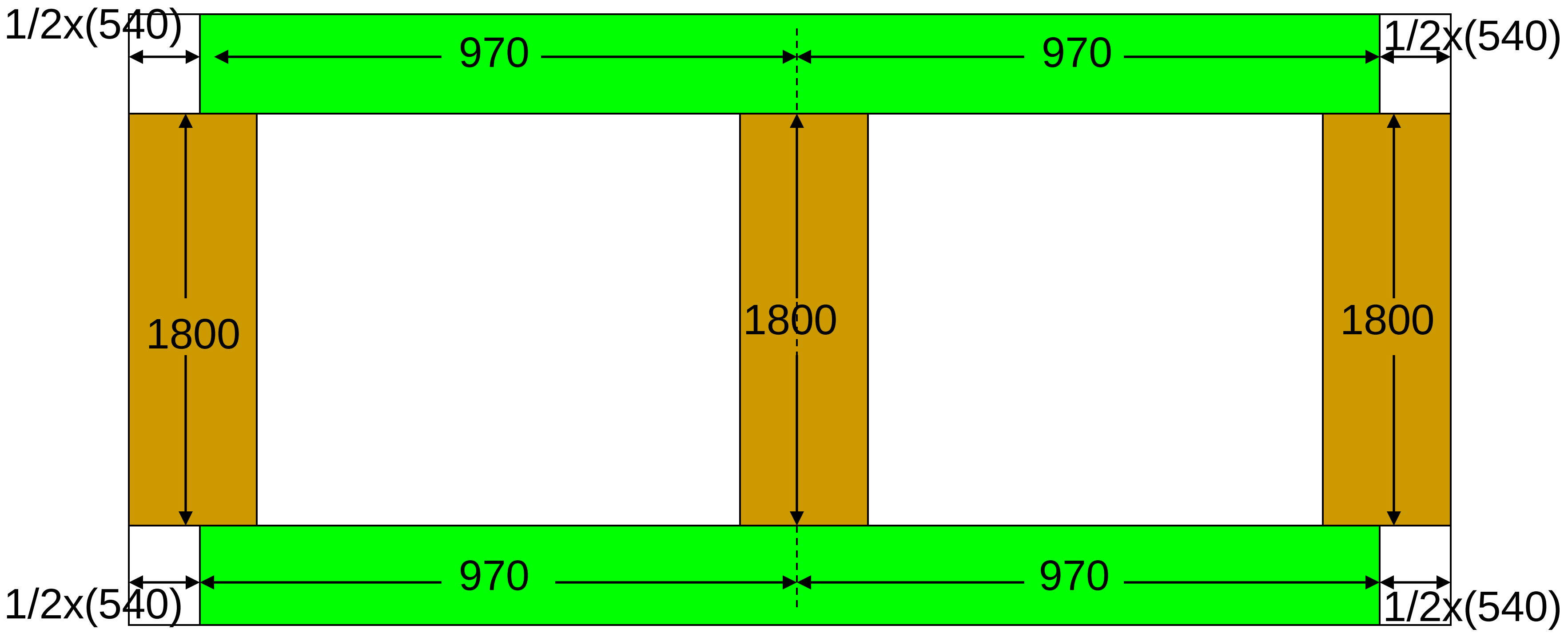
  $$= 2*54+3*180+4*97=1036 \text{ cm}$$
- Volume: $1036*2061 = 2135196 \text{ cm}^3$
- Weight (density of core lamination = $7.65 * 10^{-3}$ kg/cm^3)

  $$= \text{volume*density} = 16334 \text{ Kg}$$
- Watts/kg for built core at 1.7 tesla flux density => 1.56
- Core losses

  $$= 16334 \times 1.56 = 25481 \text{ Watts} = 25.5 \text{ kW (approx)}$$

Note: Design parameters are not optimum; values are chosen for convenience while explaining the design

Core Length Calculation:



$$\text{Length} = 4\times\left(\frac{1}{2}\times 540\right)+3\times 1800+4\times 970 \text{ mm.}$$

$$= (2\times 54+3\times 180+4\times 97) \text{ cm.}$$

Shunt Branch Parameters of the Equivalent Circuit

$$R_c = (132\times10^3/\sqrt{3})^2 / (25.5\times10^3/3) = 683.3\ \text{k}\Omega$$

$$I_c = (132\times10^3/\sqrt{3}) / 683.3\times10^3 = 0.11\ \text{A}$$

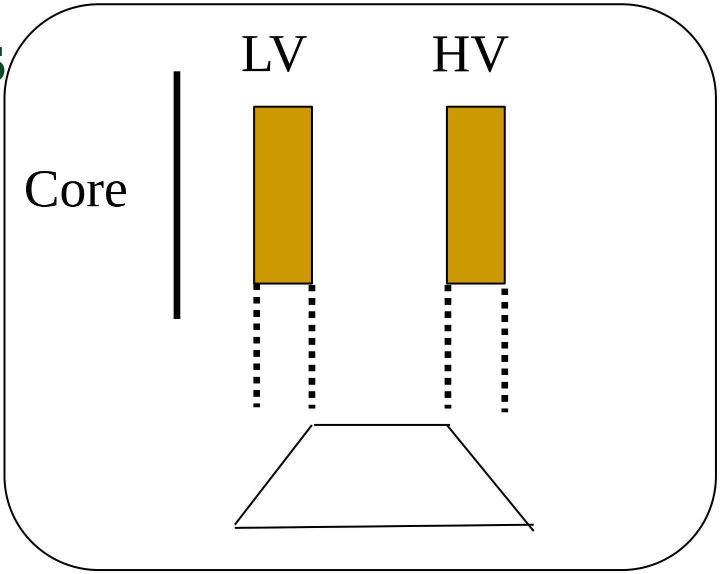
- VA/kg for built core at 1.7 tesla flux density => 9.6
- No-load current (I_0)= $(9.6\times16334) / (\sqrt{3}\times132\times10^3) = 0.69$ A
- Magnetizing current

$$I_m = \sqrt{(0.69)^2 - (0.11)^2} = 0.68\ \text{A}$$

- Magnetizing reactance

$$X_c = (132\times10^3/\sqrt{3}) / 0.68 = 112.1\ \text{k}\Omega$$

Leakage Inductance Calculations



- <u>Effective height</u>

  $= 152 + \{(HVOD\text{-}LVID)/2\Pi\}$

  $= 152 + (91.8-58.6)/(2\Pi)$

  $= 157.3$ cm $= 1.573$ m

- <u>Effective area</u>

  $= [(5.2/3)*63.8+4.9*73.9+(6.5/3)*85.3] \times \Pi \times 10^{-4}\ m^2$

  $= 657.5 \times \Pi \times 10^{-4}\ m^2 = 0.2066\ m^2$

- <u>L (referred to the HV side)</u>

  $= (\mu_0 N^2 A) / HT_{eff}$

  $= (4\Pi \times 10^{-7} \times 980^2 \times 0.2066) / 1.573 = 0.158$ H

Load Loss Calculations:

I^2R loss in LV winding

- Mean turn length = mean diameter = 0.638 * Π meters
- Total length for all 3 phases

$$L = 3*.638 * \Pi*424 = 2550 \text{ m}$$

- Resistance (R)

$= \text{resistivity} * L/(\text{area})$; resistivity $= 0.0211\times10^{-6}$ Ω-m at 75^0C

$R_{LV} = (0.0211\times10^{-6} *2550) / (106 \times10^{-6}) = 0.5076\ \Omega$

- I^2 R loss in the LV winding

$= (318.2)*(318.2)*0.5076 = 51394$ Watts = 51.4 Kw

I^2R loss in the HV winding

- Mean turn length = Π* 0.853 meters
- Total length for all three phases = 3*0.853*Π*980 = 7879 m

- $R_{HV} = (0.0211 \times 10^{-6}*7879) / (46.2 \times 10^{-6})$

  $= 3.598\ \Omega$

- I^2R loss in HV

  $= 137.78*137.78*3.598 = 68306$ watts ≈ 68.3 kW

- Total I^2R loss in windings

  $= 51.4+68.3=119.7$ kW,

- And (eddy + stray) losses = 20% extra*

- Total load loss = 144 kW

Note: * Design parameters are not optimum; values are chosen for convenience while explaining the design

- Similarly, HV winding weight

  $= 7879*46.2*10^{-6}*8.89*10^{3} = 3236$ kg
- Winding losses per phase = 144/3 = 48 kW
- Resistance of the transformer per phase referred to HV

  $= (48\times10^{3})/137.78^{2} = 2.53\Omega$
- Reactance of the transformer per phase referred to HV

  $= 2\Pi \times 50\times0.158 = 49.6\ \Omega$

Calculation of weights

- LV winding volume

  = total length of conductors * area of one turn

  $= (2550\text{ m}) * (106\times10^{-6}\text{ m}^{2})$
- LV winding weight (Density of copper $= 8.89\times10^{3}$ kg/m^{3})

  $= 2550*106*10^{-6} * 8.89*10^{3}$ kg $= 2402$ kg

Equivalent Circuit

Equivalent circuit referred to the HV side