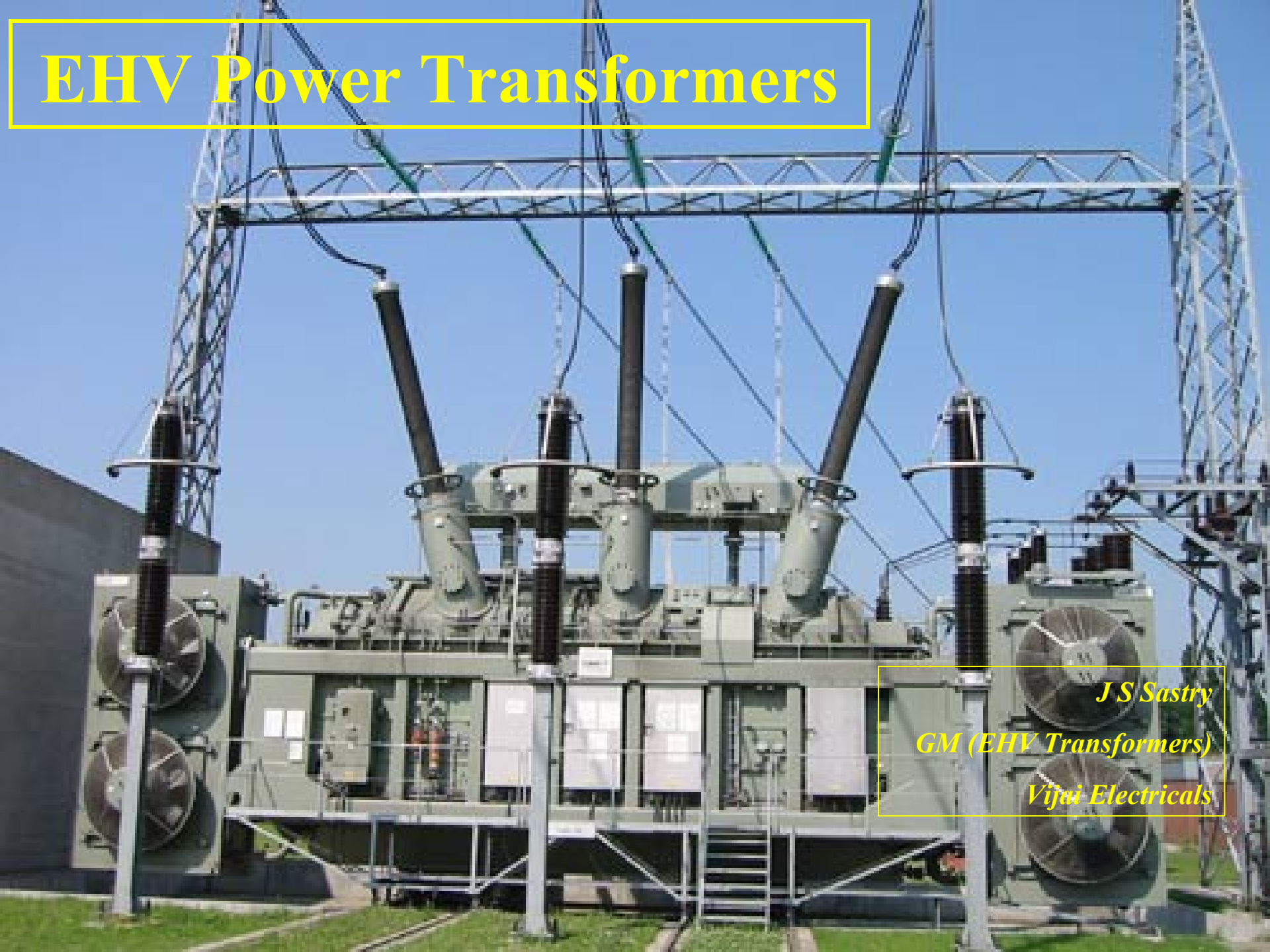


EHV Power Transformers

A large, green-painted EHV power transformer is the central focus, mounted on a metal frame. It has three prominent vertical bushings on top, each with a black insulator. The transformer is surrounded by high-voltage lines and metal structures. In the background, there are more power lines and a clear blue sky. The foreground shows a grassy area and a metal walkway leading to the transformer.

J S Sastry
GM (EHV Transformers)
Vijai Electricals

Topics to be covered

- **What is a Transformer**
- **Transformer principle**
- **Basic design concepts**
- **Construction features**
- **Materials used and improvements**
- **Types of failures and diagnostics**
- **Challenges to Transformer Designers**
- **Reactors**

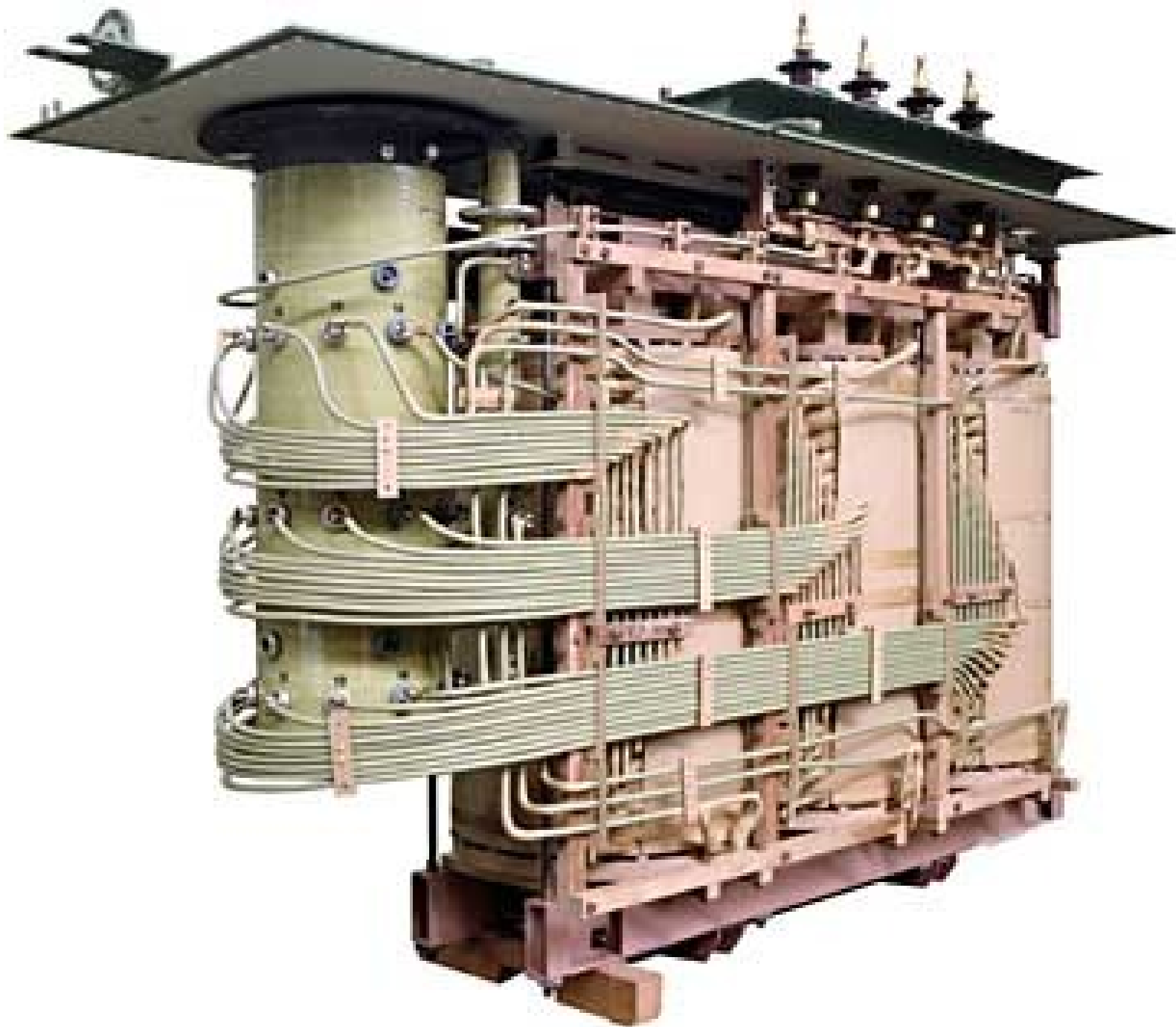


*IF YOU HAVE NO DOUBTS
YOU HAVE NOT
UNDERSTOOD ANYTHING.*

- a Spanish proverb.

What is a Transformer

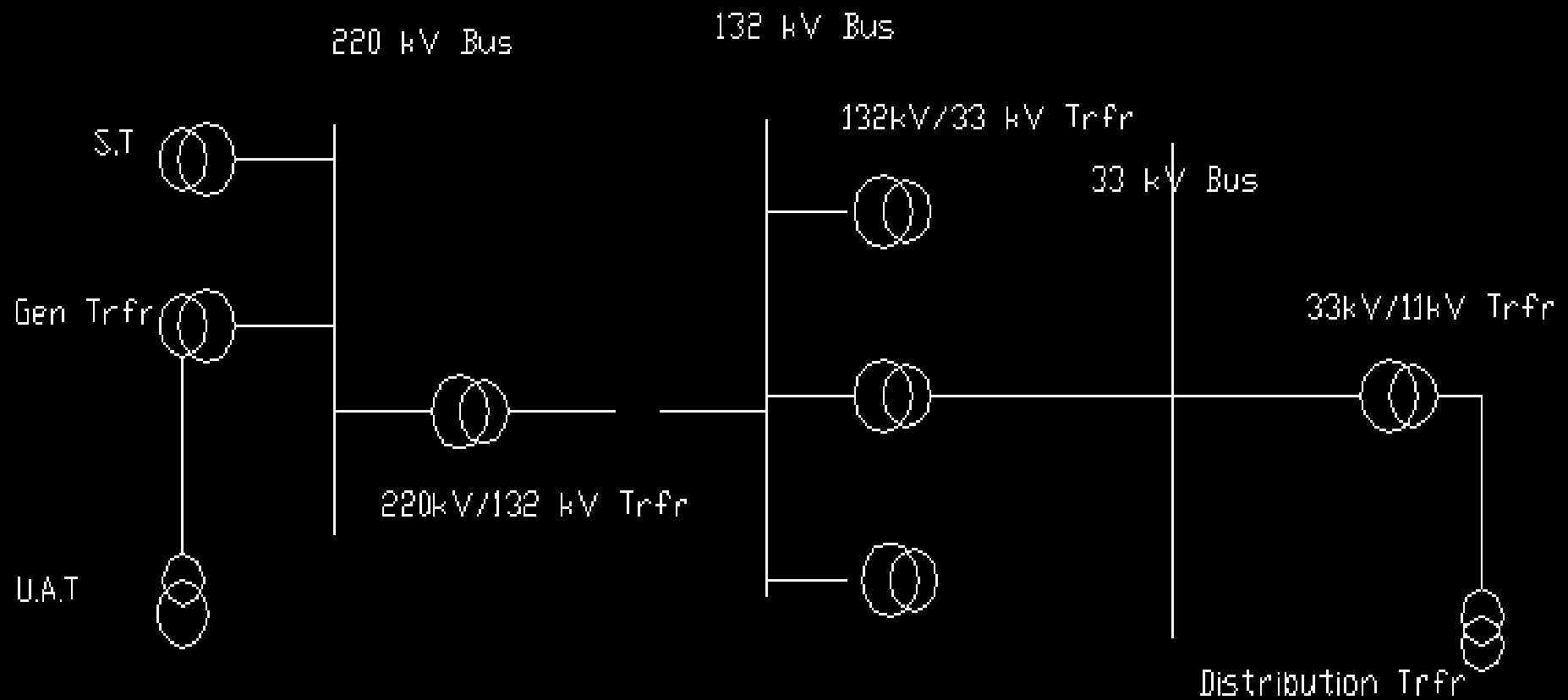
- **A transformer is a static equipment which transforms power from one circuit to another by stepping up or down the primary voltage without any change in the frequency.**
- **The two circuits may or may not be connected but are magnetically coupled.**



Features of Power Transformers

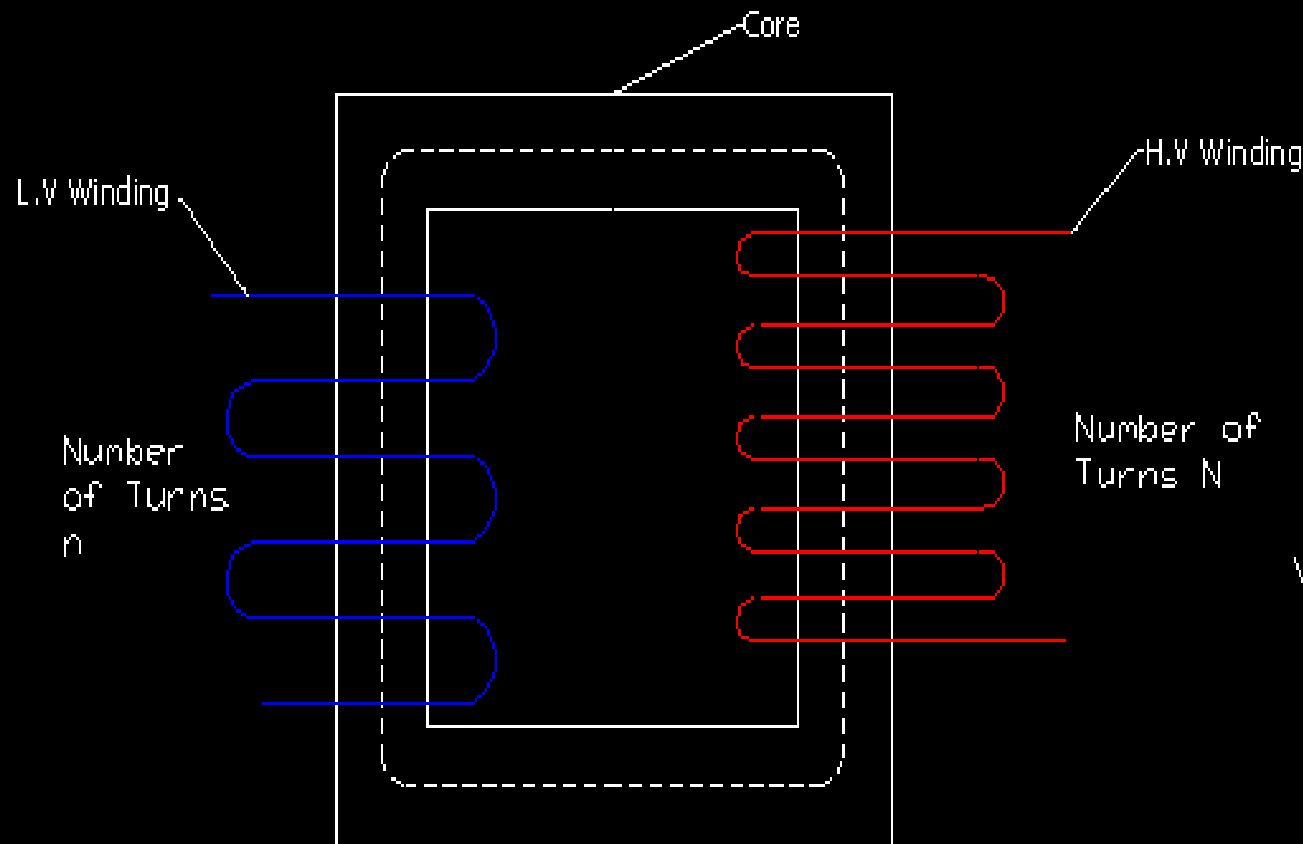
- **Single Phase**
- **Three phase**
 - **Star or Delta connected Primary**
 - **Star or Delta connected Secondary**
 - **With or without Tertiary winding**
- **Provided with Off-circuit tap switch or On-load Tap Changer for voltage regulation**

Transformers in Network



Transformers in a Network

Transformer Operating Principle



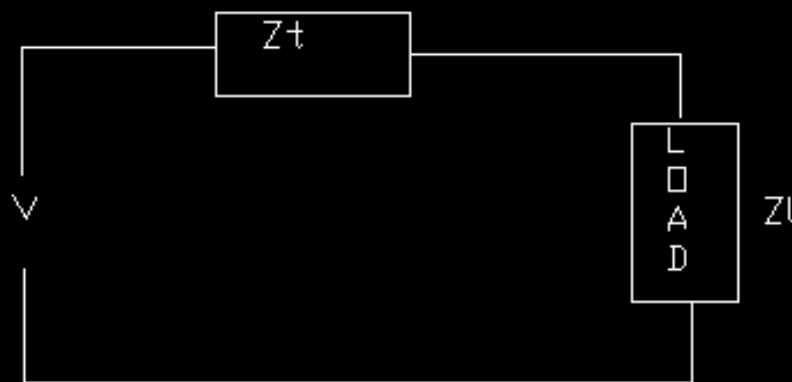
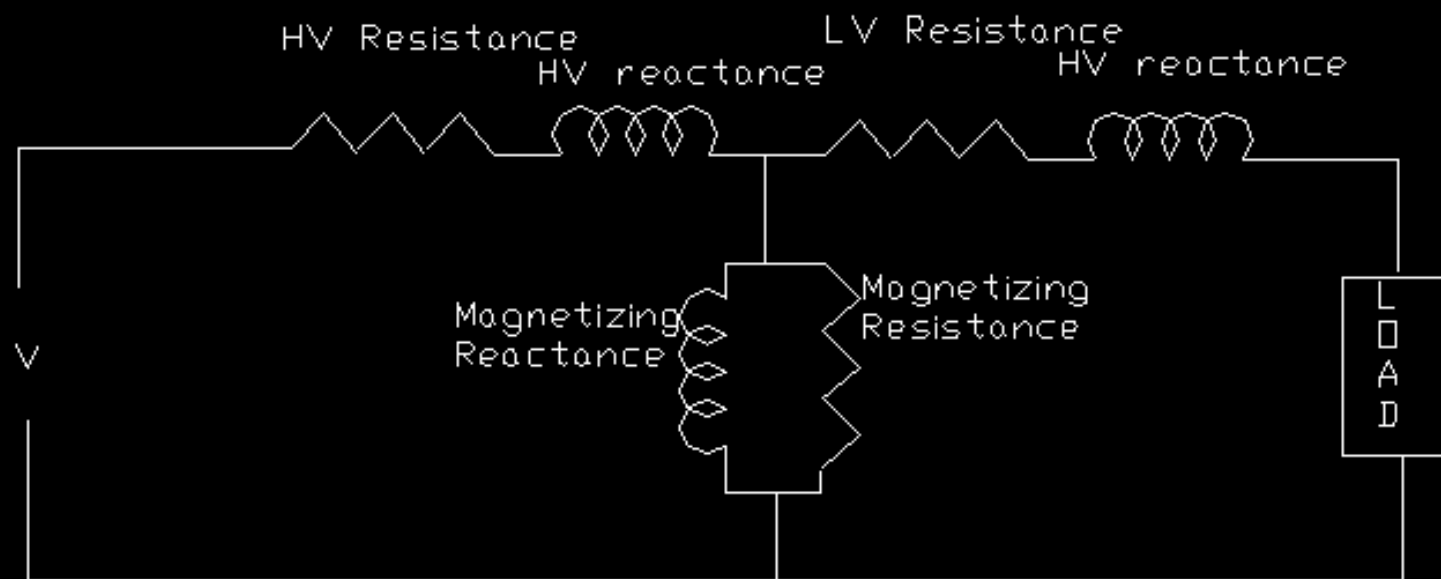
TRANSFORMER FUNDAMENTAL EQUATIONS

Core Area : A
Core Flux Density: B
Frequency: f
H.V. Voltage : V
Transformation Ratio: M
L.V. Voltage $v = V/M$

$$\text{Volts/turn} = 4.44 \times f \times B \times A \times 10^{-8}$$

Operating Principles

Equivalent Circuit



Neglecting magnetizing Impedance,

$$\text{Line Current} = \frac{V}{Z_t + Z_l}$$

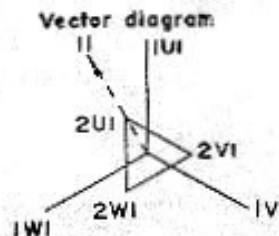
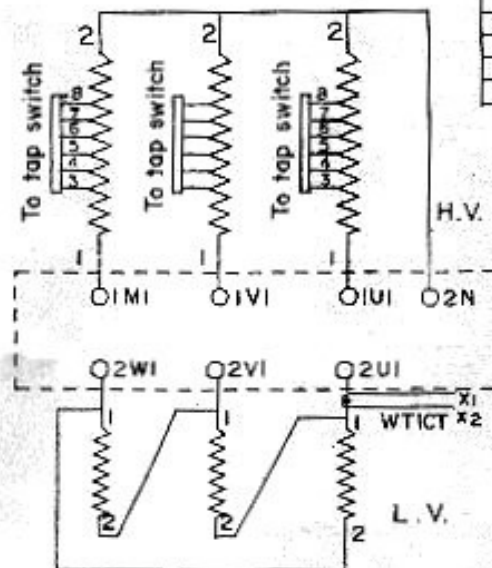
$$\text{Short Circuit Current} = V/Z_t$$

Power MVA	{	HW	Type of cooling	{	Oil	{	
Voltage at no load kV		LV	Guaranteed maximum temperature rise				
Line current AMPS	{	HW	Makers spec. No.	{		{	
		LV	Makers sr. No.				
		LV	Year of manufacture				
Phases			Untanking mass (Core & winding)				
Frequency			Total oil				kg
Vector symbols			Total mass				kg./litres
Diagram Drg. No.			Heaviest package	{	With oil		kg
Oil circulation	L/MIN				Without oil		kg
Water circulation	L/MIN						kg.

LI	AC	LI	AC
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HV kV	Switch diagram	Leads connected	Impedance voltage H.V.-L.V. %

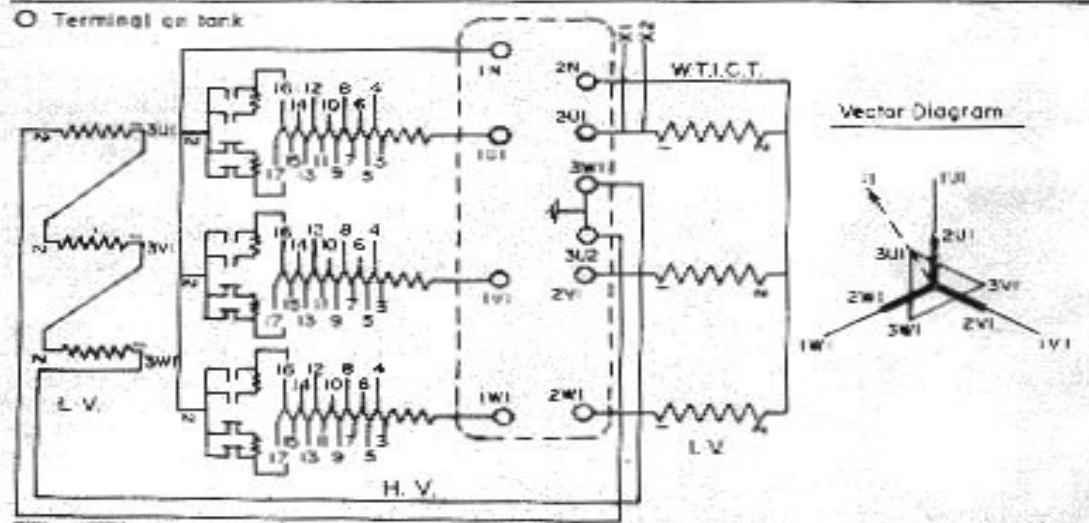


(1) The tank is suitable for _____ vacuum

Specification Parameters for Generator Transformer

**TRANSFORMER
TO INDIAN STANDARD 2026-1977/1981**

Power MVA			
Voltage of no load kV			
Line current Amps			
Phases			
Frequency			
Vector symbols			
Diagram drg. No.			
Insulation level	LI AC LI AC /LI AC LI AC /LI AC		
Type of tapchanger			
Customers reference			
Transformer manufacturers name			

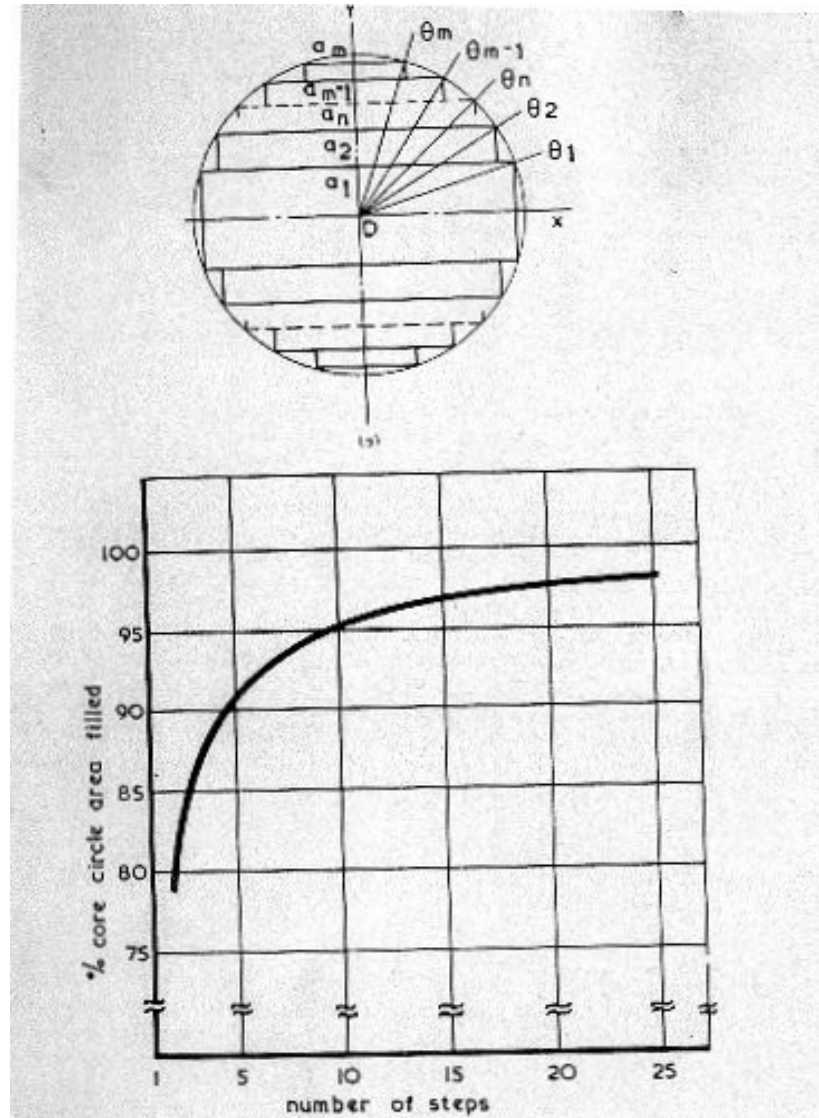
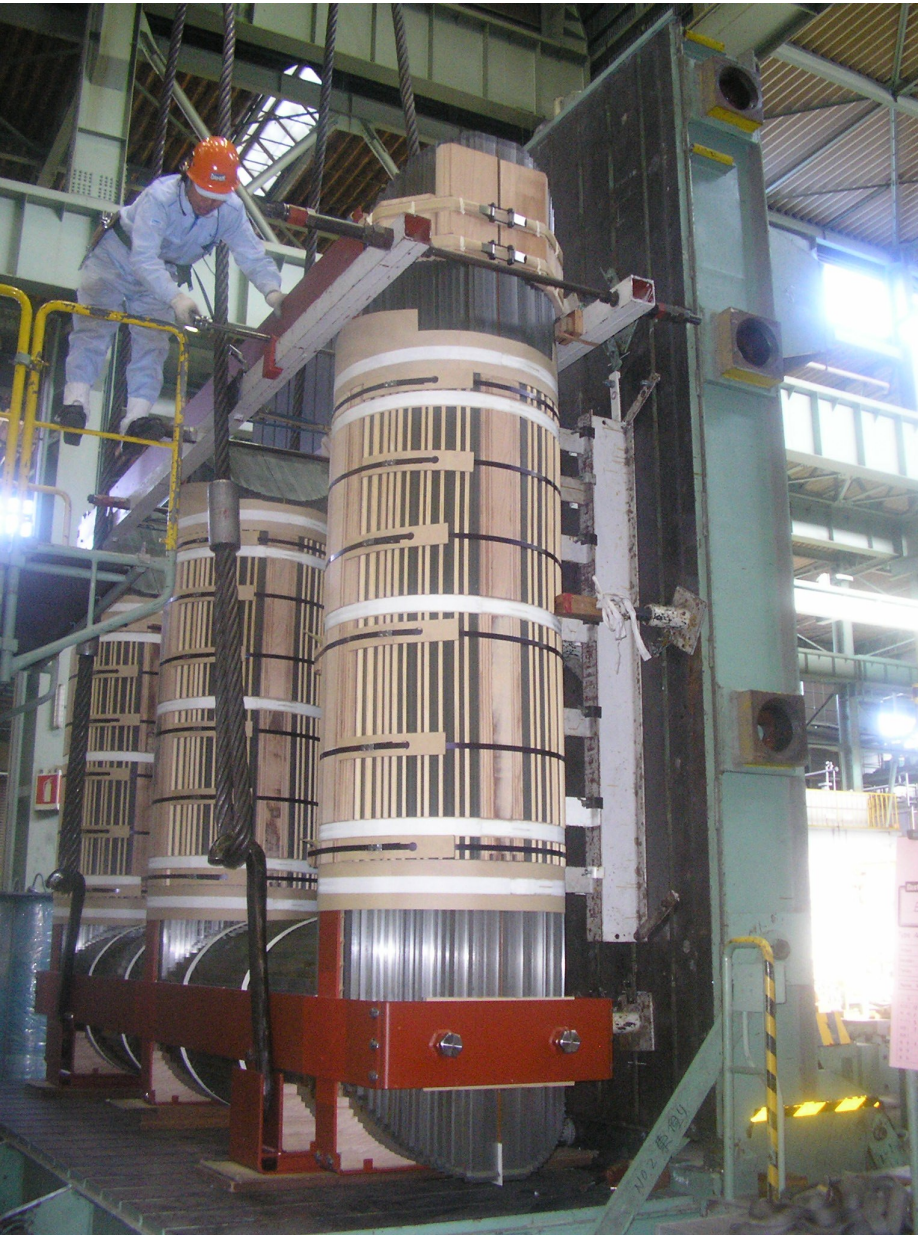


H.V. KV	Tap changer position	Leads connected	Impedance HV-LV %	Voltage %
118-17	1	2-17		
120-18	2	2-16		
121-43	3	2-15		
122-46	4	2-14		
123-69	5	2-13		
124-74	6	2-12		
125-95	7	2-11		
126-100	8	2-10		
127-105	9	2-9		
128-125	10	2-8		
129-31	11	2-7		
130-52	12	2-6		
131-57	13	2-5		
132-62	14	2-4		
133-63	15	2-3		

Oil or Air Cooling
Oil circulation litres per minute
Air circulation cubic metre per minute

Specification
Parameters
for Network
Transformer

Design Principles - Core

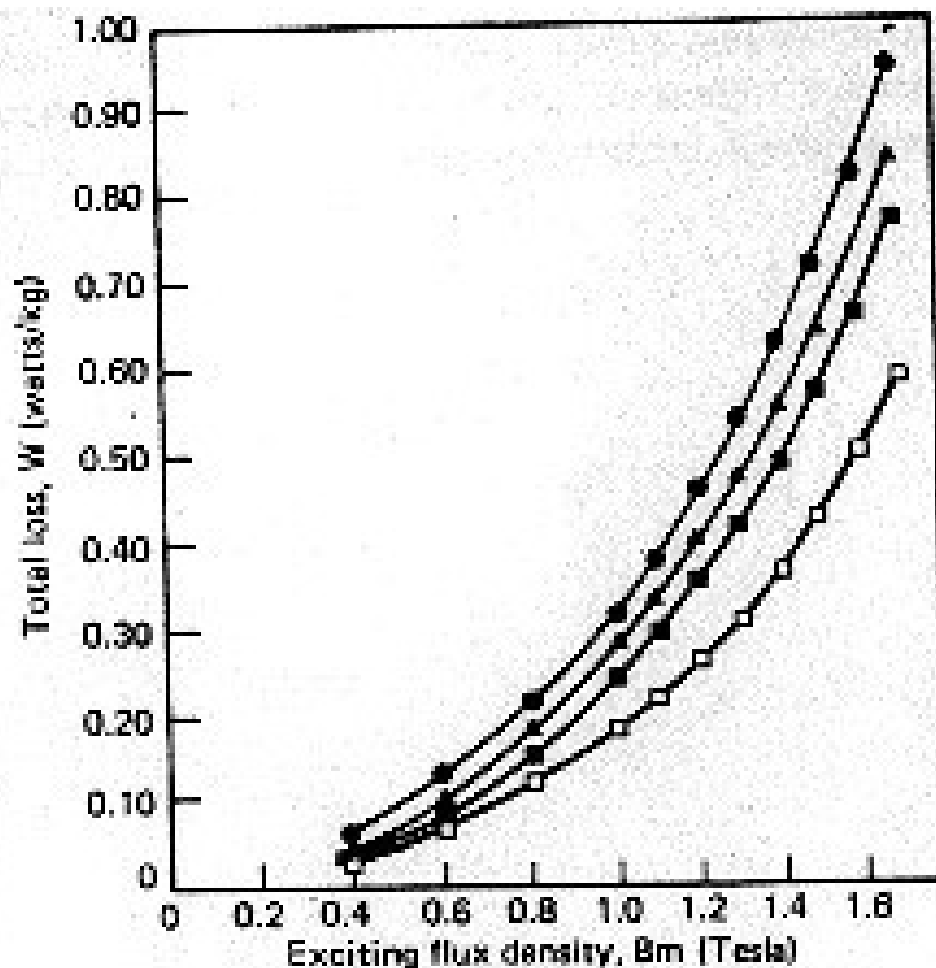


Design Principles - Core

- Higher the number of steps in cross section, better is space utilization and smaller is the core diameter.
90 to 95 % utilization factor is optimal.
- Core area (A) is determined by the Flux Density (B) which in turn depends on many factors - like loss capitalization and overall design economics.
- As the no load losses attract very high capitalization, attempts are continuously made to reduce them.

Design Principles - Core

- Improved manufacturing techniques like core building with 2-lamination packets, step-lap joints, v-notched laminations, bolt-less cores are used.
- Hi- β core steels like M0H, ZDKH, etc are available in which the specific core losses are lower than normal grades.
- Amorphous steels drastically reduce no-load losses, but are now being used only in distribution transformers.



- 0.30 mm HI-B (3.25% Si, commercial product)
- ▲ 0.23 mm HI-B (3.25% Si, commercial product)
- 0.15 mm HI-B improved (laboratory)
- laser-irradiated 0.15 mm HI-B improved (laboratory)

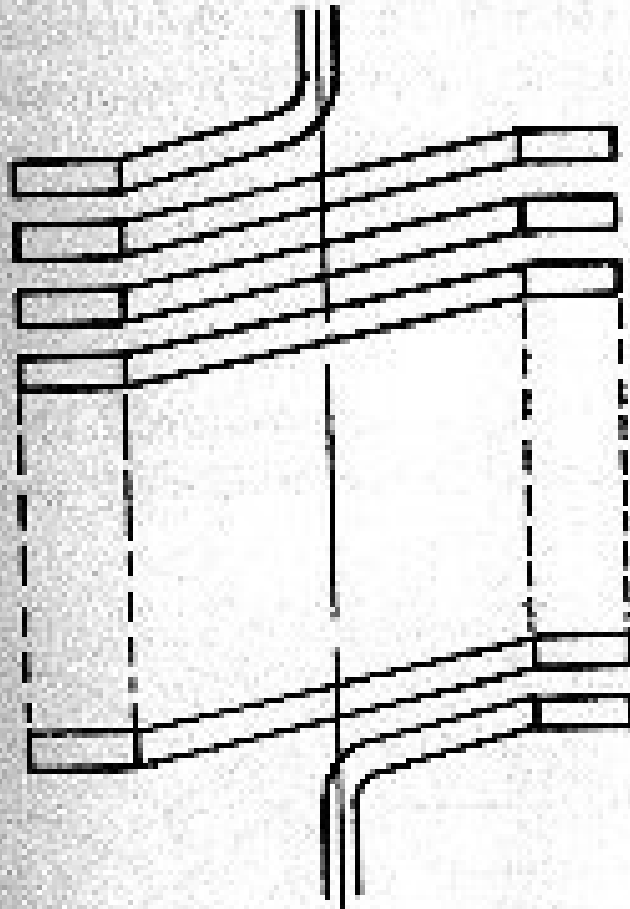
Correlation between losses and thickness

Design Principles

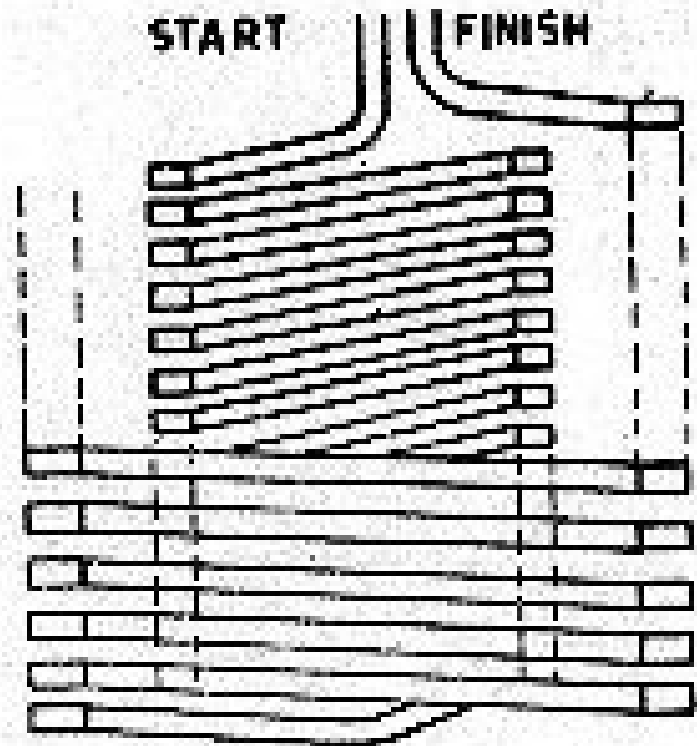
Windings- L.V winding

- ❖ **L.V Windings in Transformers are either**
 - ❖ **Spiral wound for for low current ratings**
 - ❖ **Helical Wound with radial cooling ducts for higher ratings.**
- ❖ **The conductor used is paper insulated rectangular copper (PICC)**
- ❖ **For higher currents, transposed conductors are used, to uniformly distribute the current across the cross section of the wire of coil.**

Design Principles- L.V winding



Helical coil (single layer)



Helical coil (double layer).

Design Principles

H.V Winding/1

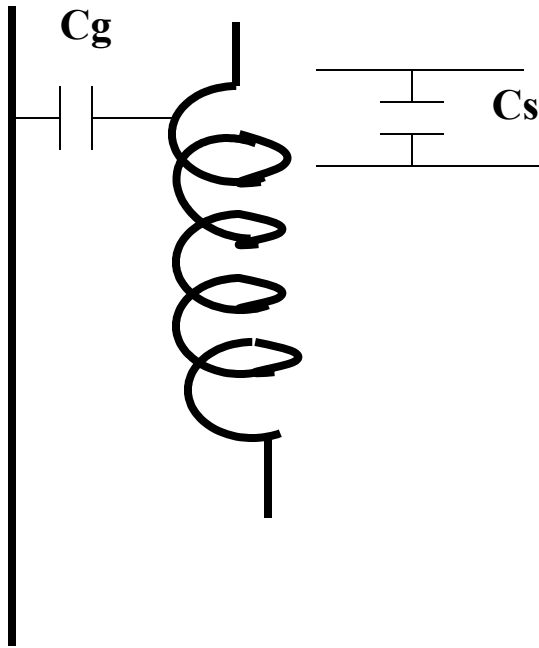
HV winding is invariably uses PICC or CTC.

Type of winding used is

- Disc winding up to 132 kV
- Layer winding or
- Interleaved winding or
- Rib shielded winding

Design Principles

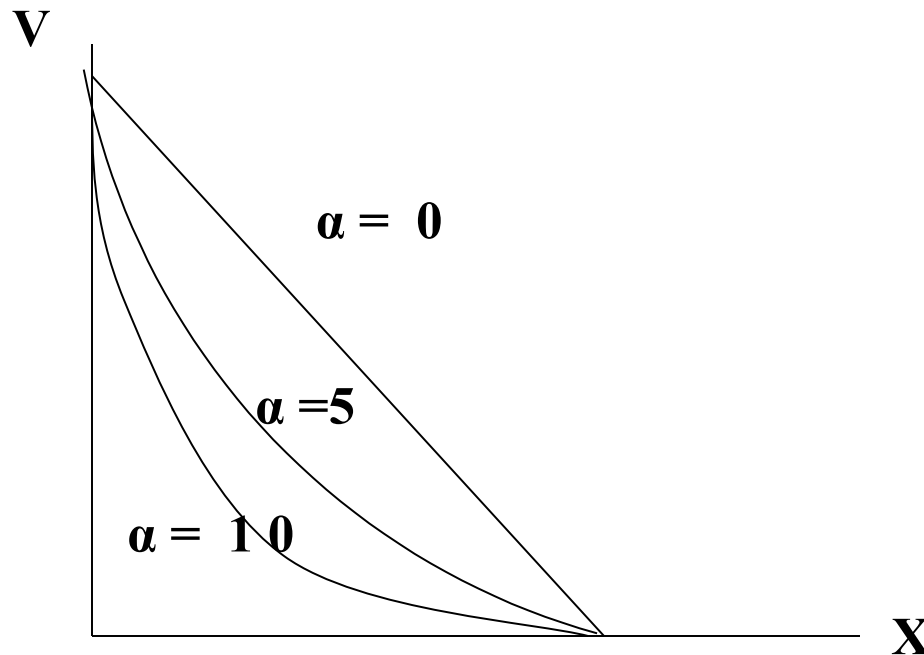
Impulse Voltage Distribution



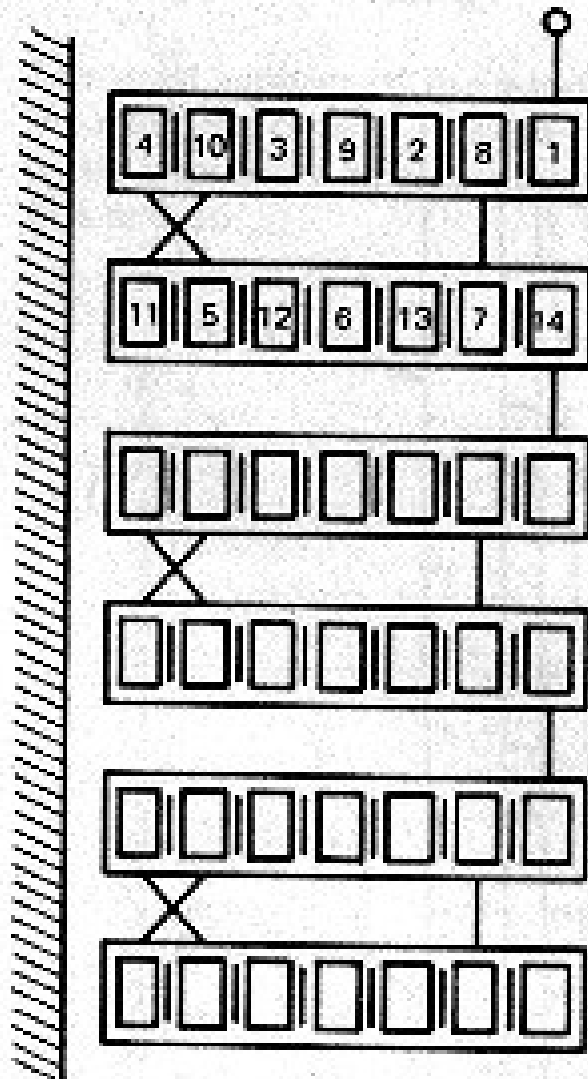
$$\alpha = K \sqrt{C_g/C_s}$$

Design Principles

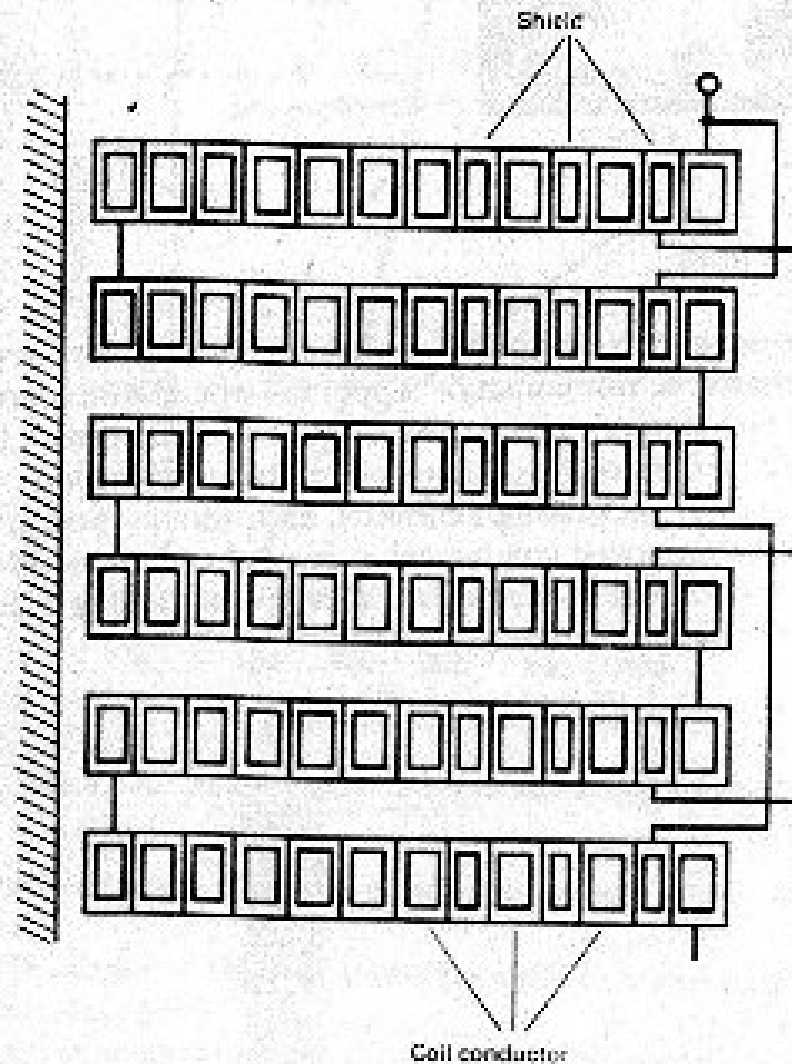
Impulse Voltage Distribution



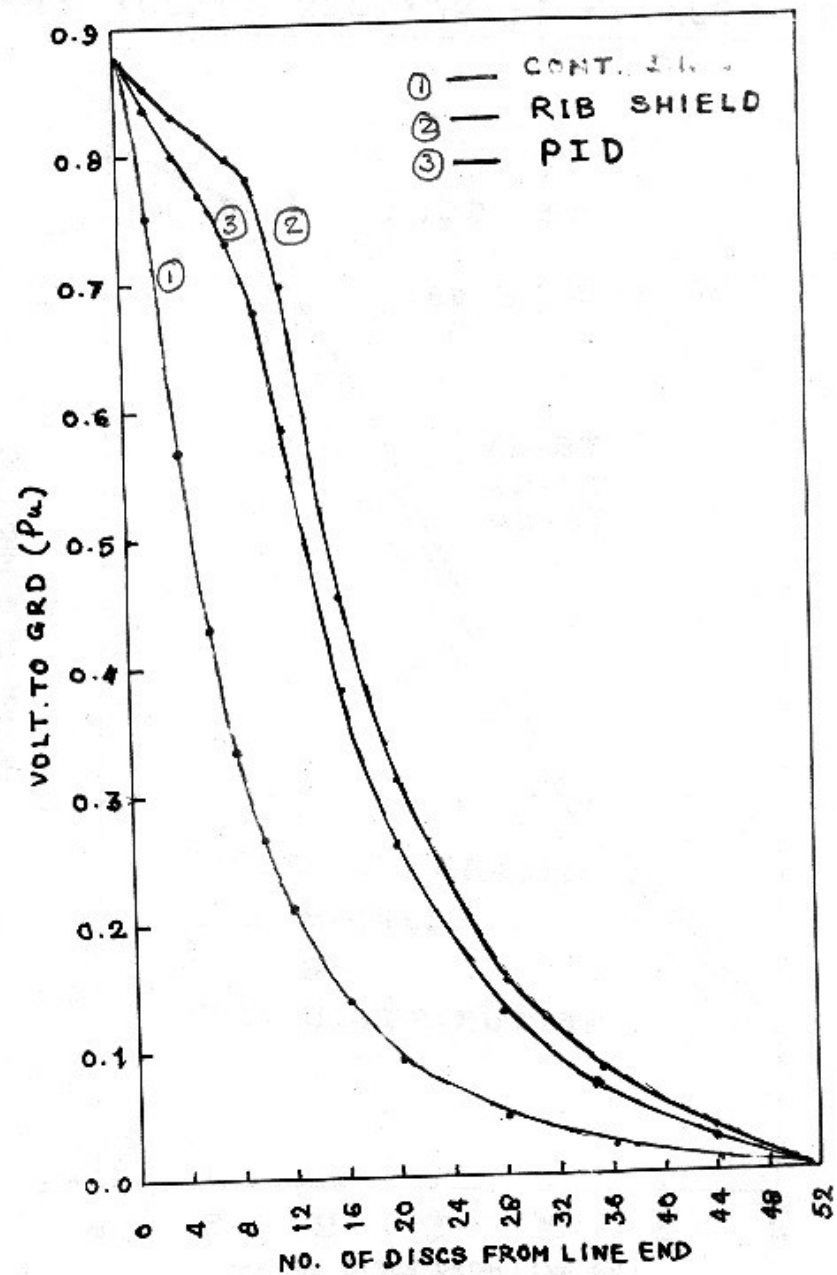
Windings - Interleaved winding



Windings - Rib Shield Winding



IMPULSE VOLT. DIST. IN HV WINDING



Design Principles

Tertiary Winding/1

In Star-Star Connected Transformers and Auto-transformers, Tertiary Winding is used-

- to stabilize phase to phase voltages in case of unbalanced load**
- Suppressing third harmonic currents in earthed neutral**
- reducing zero sequence reactance**
- for supplying auxiliary load or for connecting capacitors.**

Design Principles

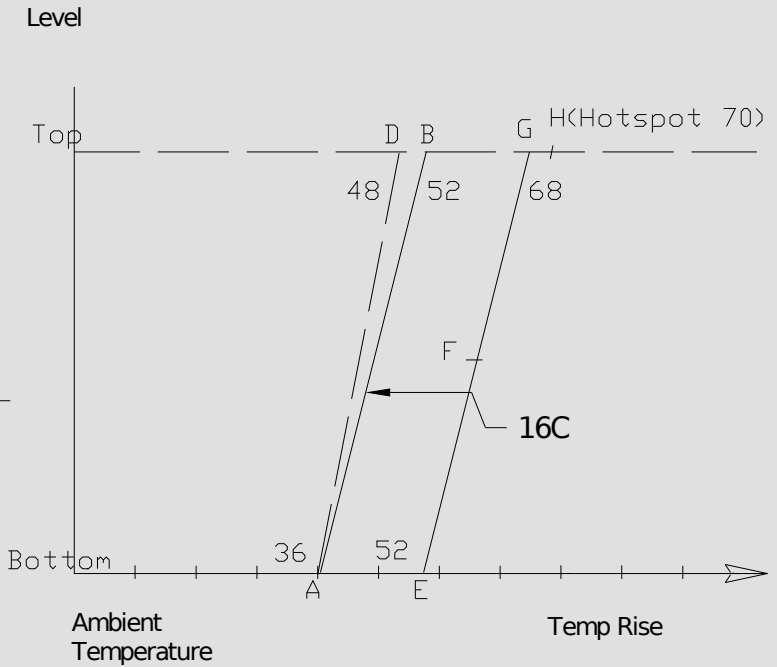
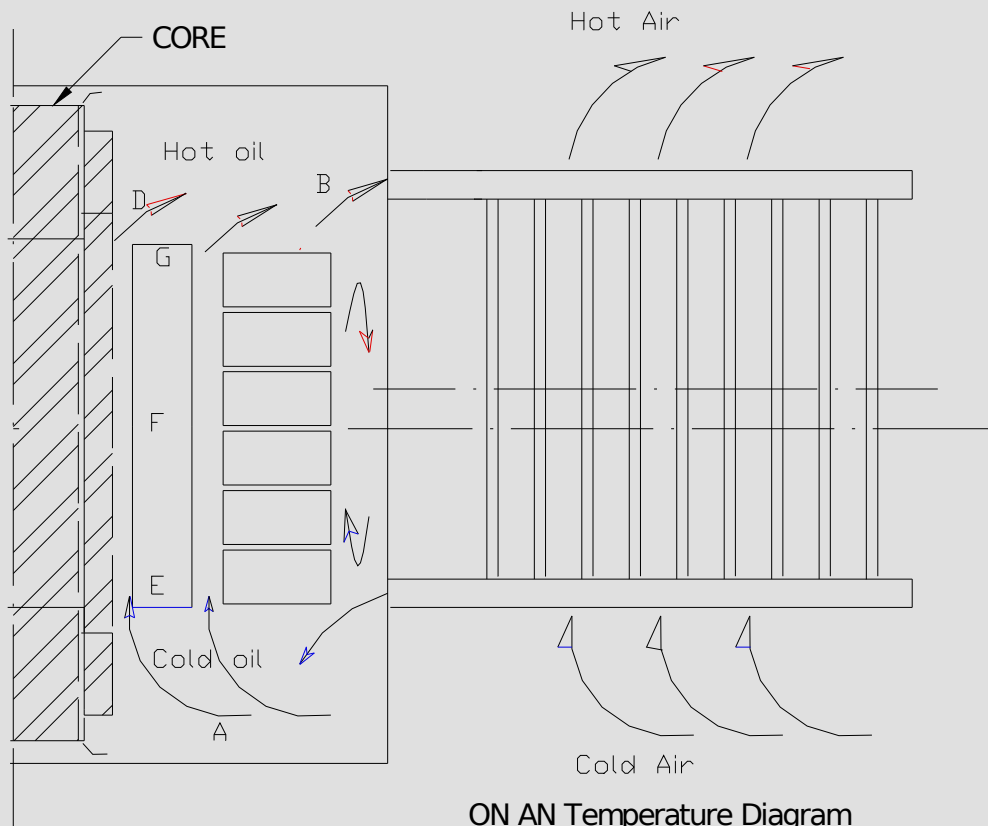
Tertiary Winding/2

- ❖ Tertiary is required to be designed for a power rating equal to one-third the rated power, it increases the cost of the transformer by 10- 12 percent.
- ❖ Tertiary winding is known to fail due to transferred surges and Short circuits
- ❖ Present practice is to do away with tertiary up to 100 MVA for 3 phase 3 limbed core transformers.

Design Principles

Cooling

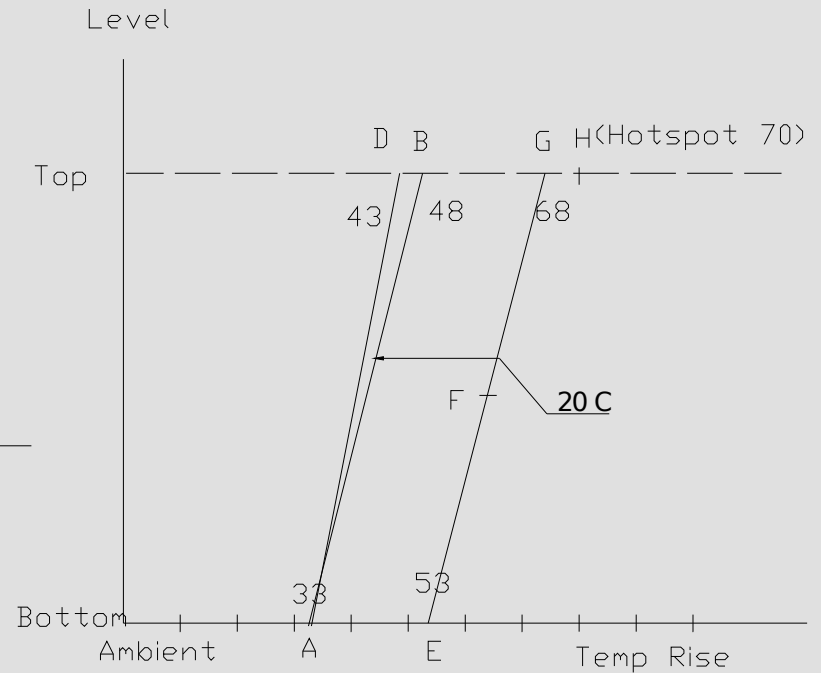
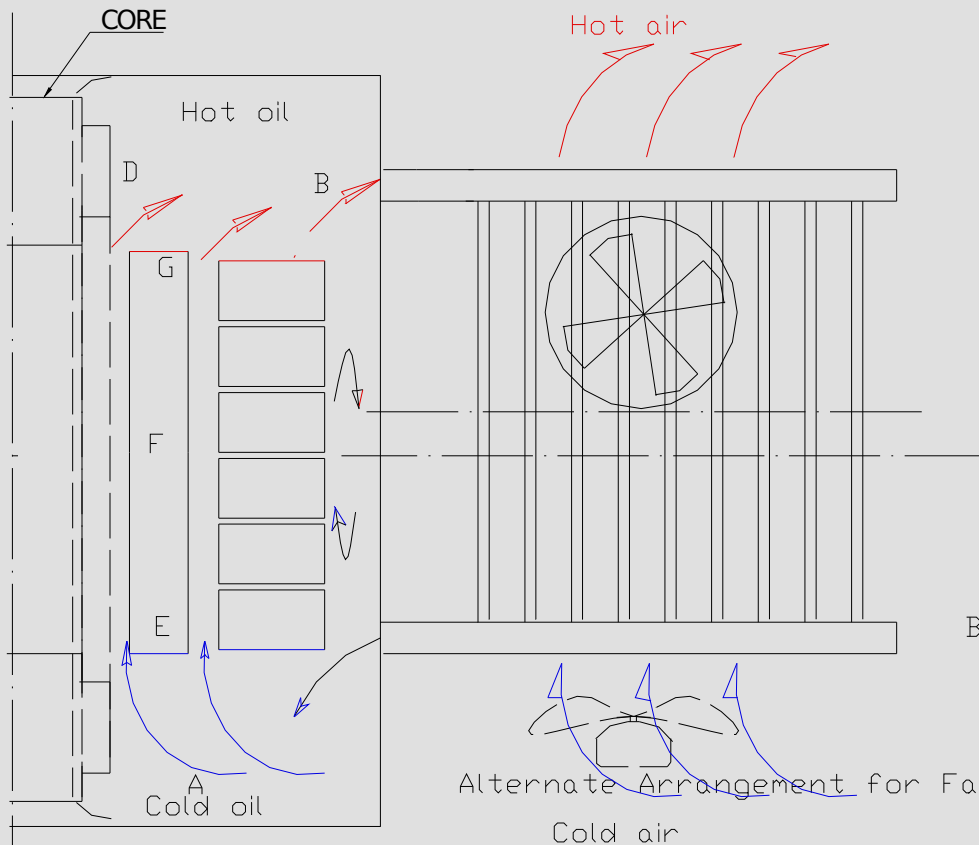
Most Common Cooling Methods	Symbol
Natural Circulation of Air and Oil	ONAN
Natural Oil Circulation and forced Air Circulation	ONAF
Forced Oil and Forced Air Circulation	OFAF
Forced Air Circulation and Directed Oil Flow through Windings	ODAF



ON AN Temperature Diagram

AD- Oil in cooler AB- Oil in winding EF - Copper in winding

AE = BG -Winding oil gradient H- Hot Spot F-Average winding temp

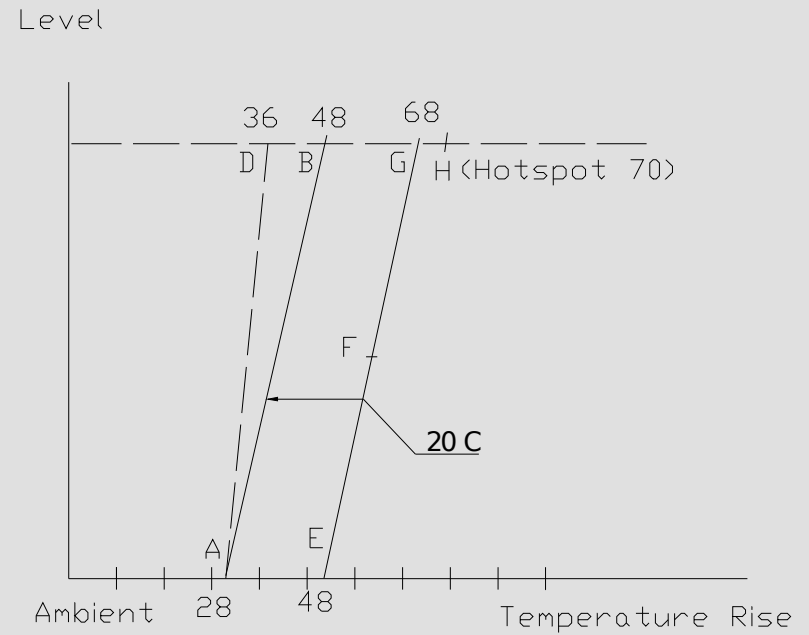
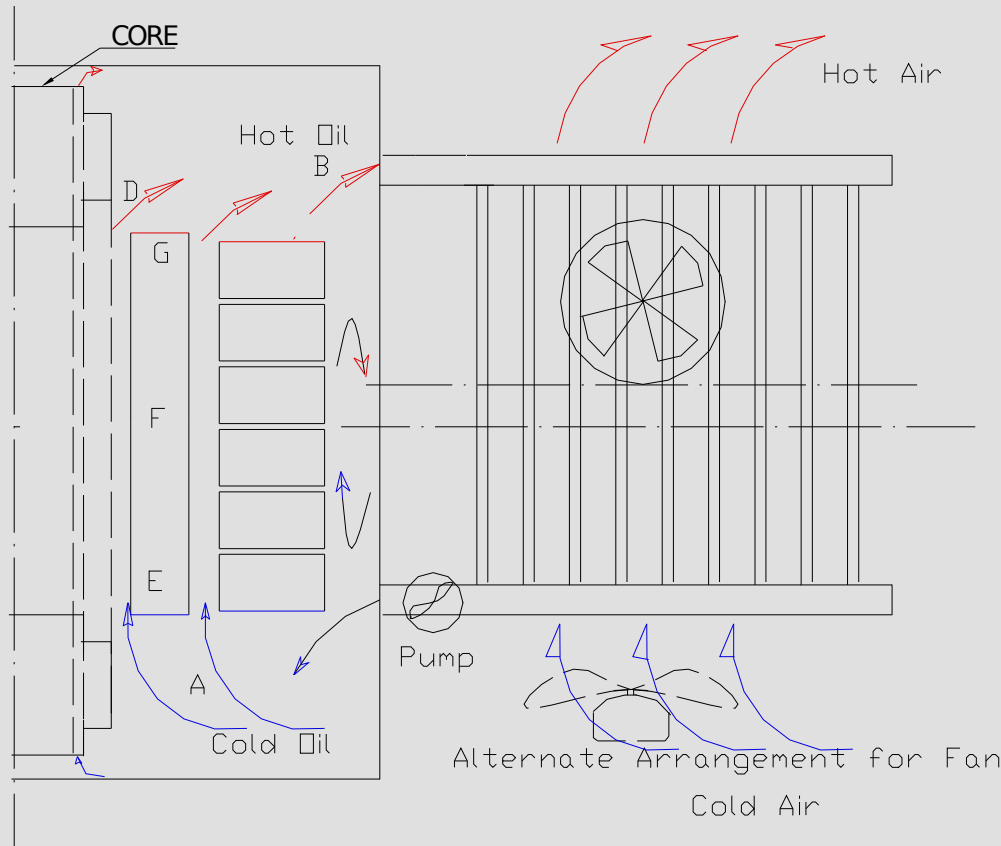


ON AF Temperature Diagram

AD- Oil in cooler AB - Oil in winding FG - Copper in winding
 H - Hot Spot AE= BG -oil winding gradient F- Mean oil temp

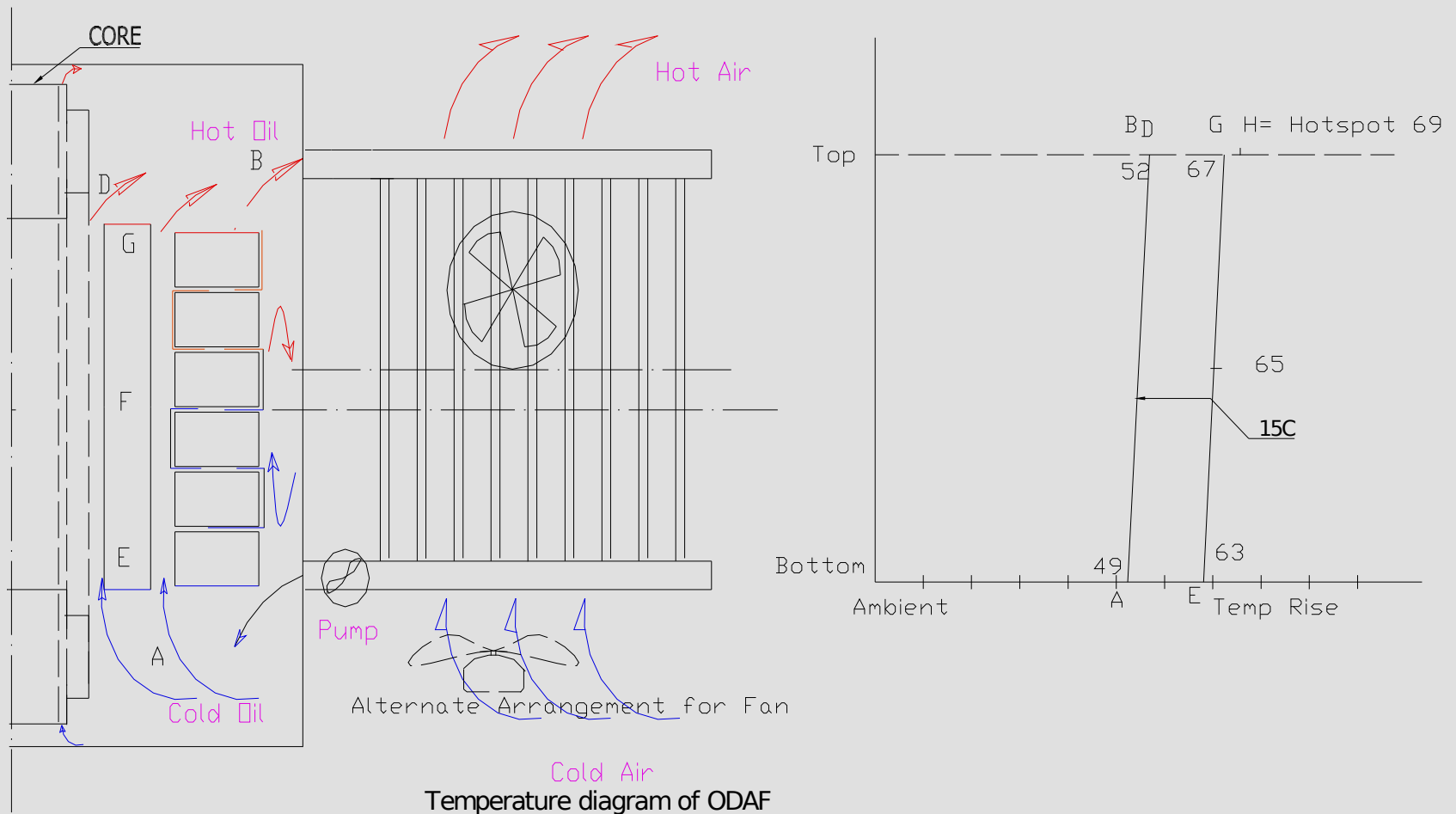
Loading and cooling 2

Effect of cooling improved by fans.



OF AF Temperature Diagram
 AD-oil in cooler, AB-oil in winding, EG-copper in winding
 H- hotspot F- average temperature of copper AE=BG copper oil gradient

Effect of cooling improved by pumps.



By canalizing oil in the radial ducts, effect of cooling further improves. Velocity of oil in windings increases several times.

Design Basis - Capitalization

CBIP Capitalization Formula:

**Capitalized Cost = Initial Cost (IC) + Capitalized
{ No-load Loss (N) + Load Loss (L) + Auxiliary
Losses (A) }**

$$\text{Capitalized Cost} = IC + C_n.N + C_l.L + C_a.A$$

Factors affecting C_n ; C_l and C_a

Rate of Interest

Rate of Electrical Energy

Life of Transformer

Design Principles

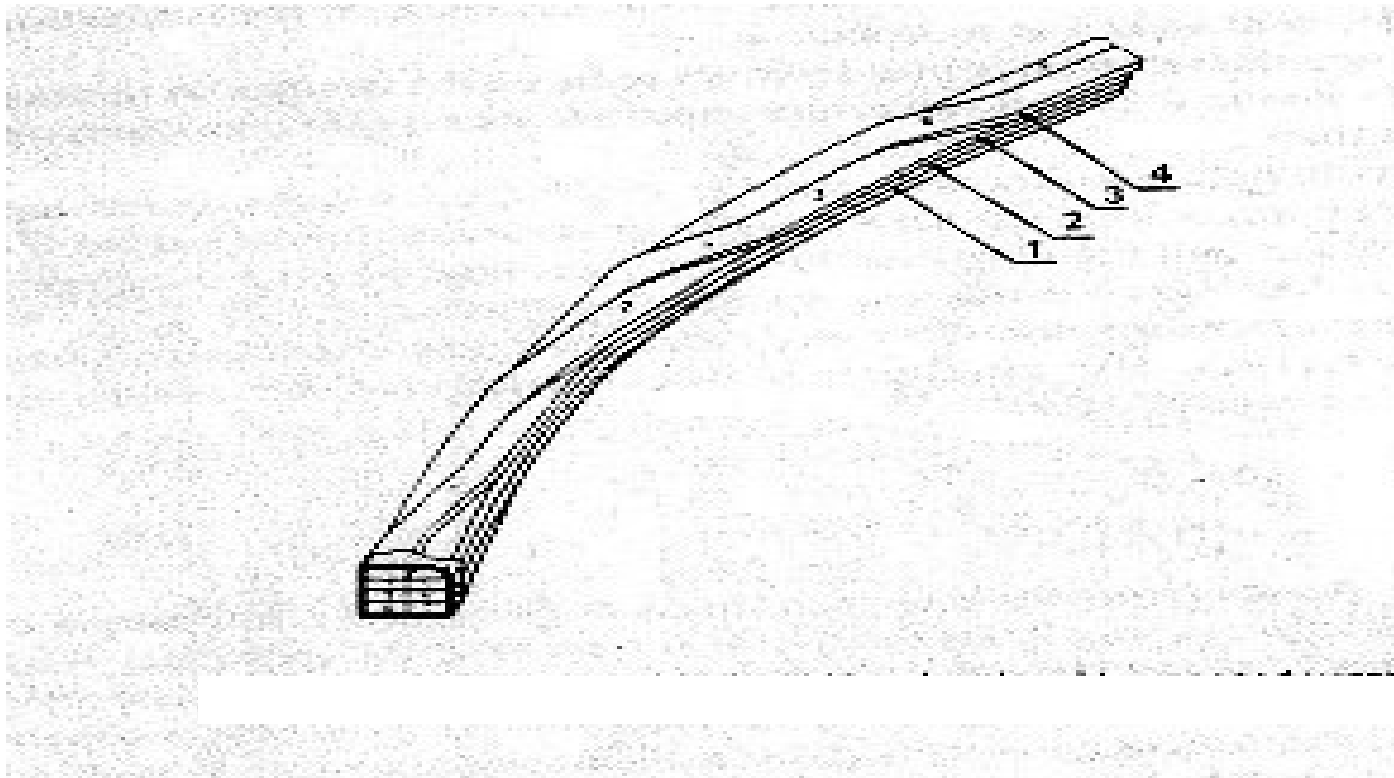
- **The design of a transformer aims at achieving lowest capitalized cost.**
- **Low Iron Loss means higher magnetic material cost but lower capitalized cost and vice-versa**
- **Low Load Loss means higher material cost but lower capitalized cost and vice-versa.**
- **Extensive use of digital computer programs is needed for finalizing design.**

Improvements in Materials

Transposed Conductors

Transposed conductors (CTC) are used to improve current distribution in the cross section of the winding wire.

Individual cable can be coated with epoxy so that the cured and finished conductor is mechanically stronger and withstand short circuit forces better.



Improvements in materials

Insulating Paper

- ✓ **Insulating Paper continues to be Cellulose Kraft Paper (Temperature Class 135°C)**
- ✓ **Thermally upgraded paper (Nomex , Aramid 155°) is used in hot spot regions in transformers with space constraints, like Traction Transformers.**

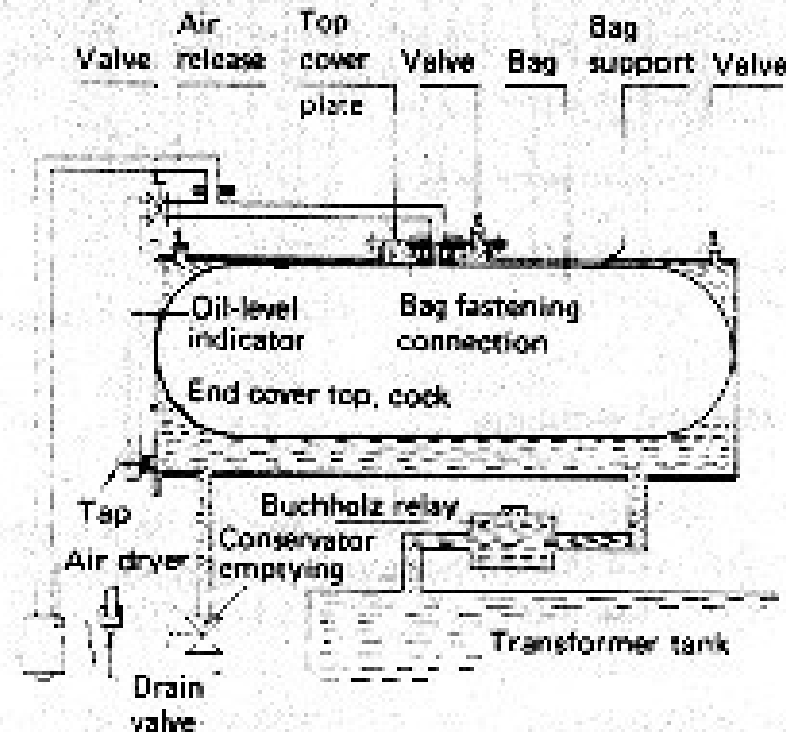
Improvements in Materials

Insulating Oils

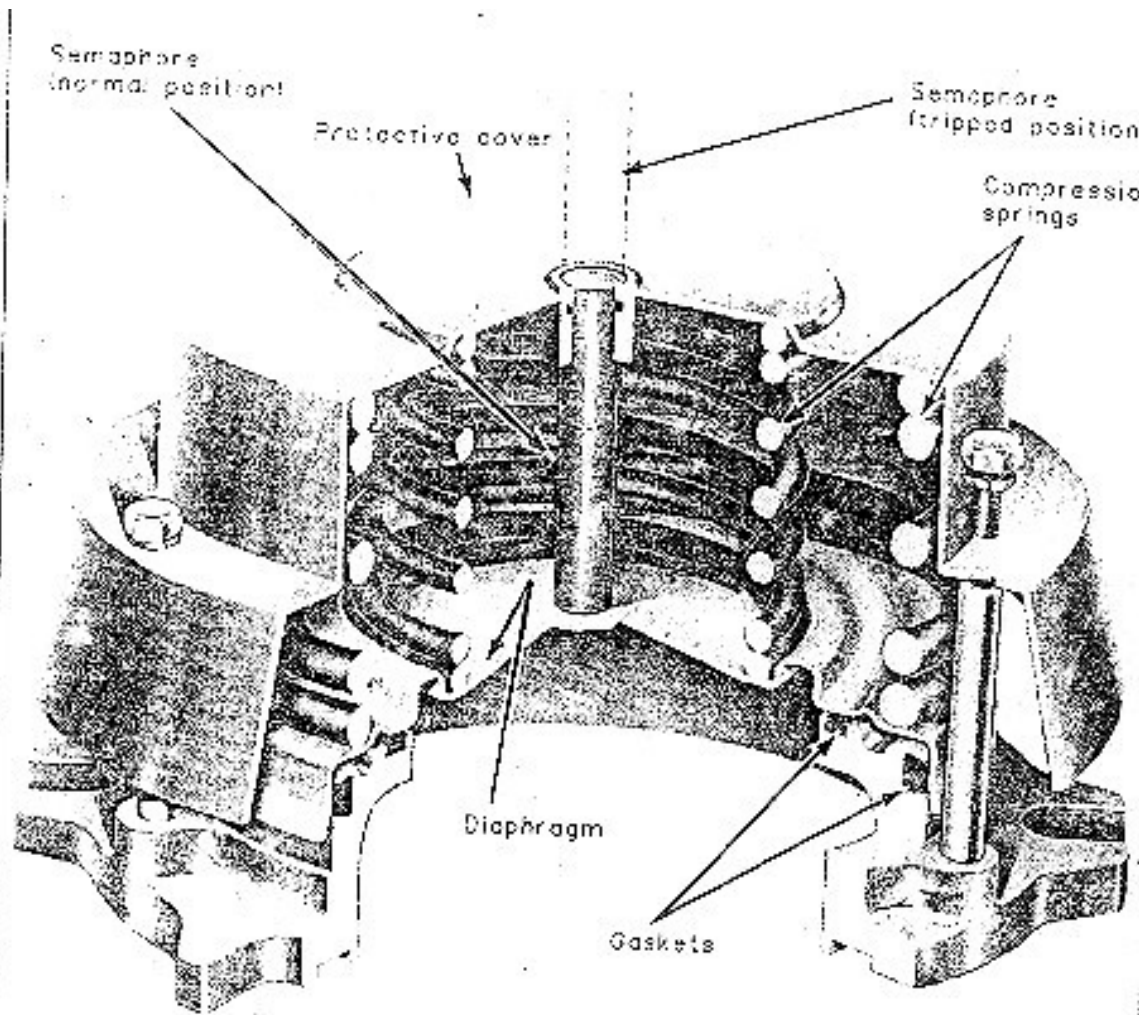
- **Paraffin T.O.B.S Based transformer oil is used in almost all Transformers in India. Naphtha based transformer oils are available.**
- **Silicone Fluids are used in regions where fire hazard is present- e.g., E.S.P Transformers. Silicones are low viscosity fluids and require special processing plant- besides new types of gaskets and components.**

Improvements in Materials

Sealed Conservators



PRESSURE RELIEF DEVICE



BUSHINGS

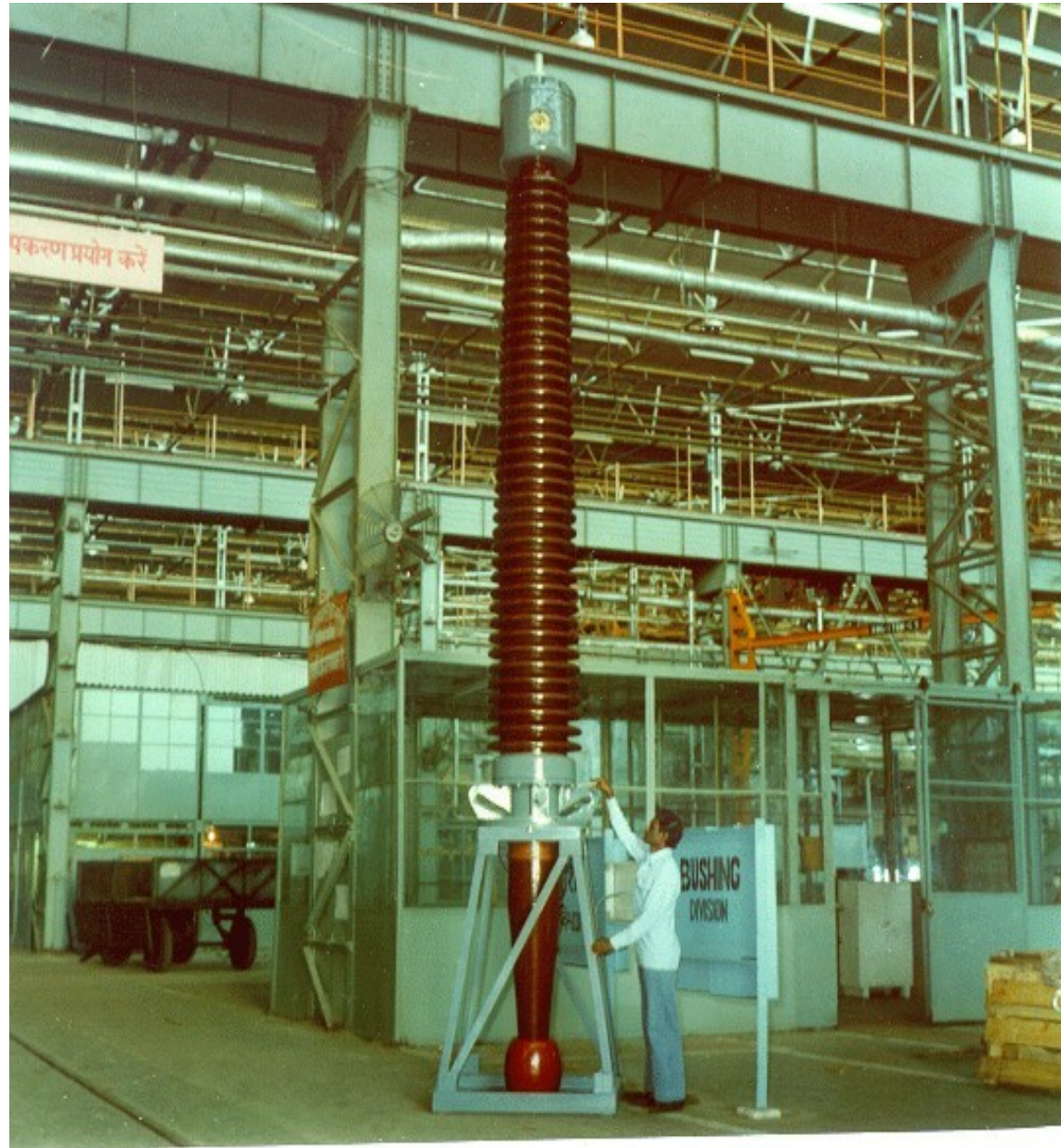
SRBP



OIP



RIP



Poor Quality of Processes

*Design or
Production or
Maintenance*

results in ...

Types of failures

- ☹ **Infant failures: Early life failures are the result of latent or delivered defects.**
 - **Latent defects are abnormalities that cause failure, depending on degree of abnormality and amount of applied stress.**
 - **Delivered defects are those that escape test / inspection within the factory**
 - **They are directly proportional to total defects in the entire processes.**

Types of failures

- ☹ **Mid life failures: These are results of –**
- **Freak system disturbances**
 - **Wrong specifications**
 - **Poor maintenance**

Types of failures

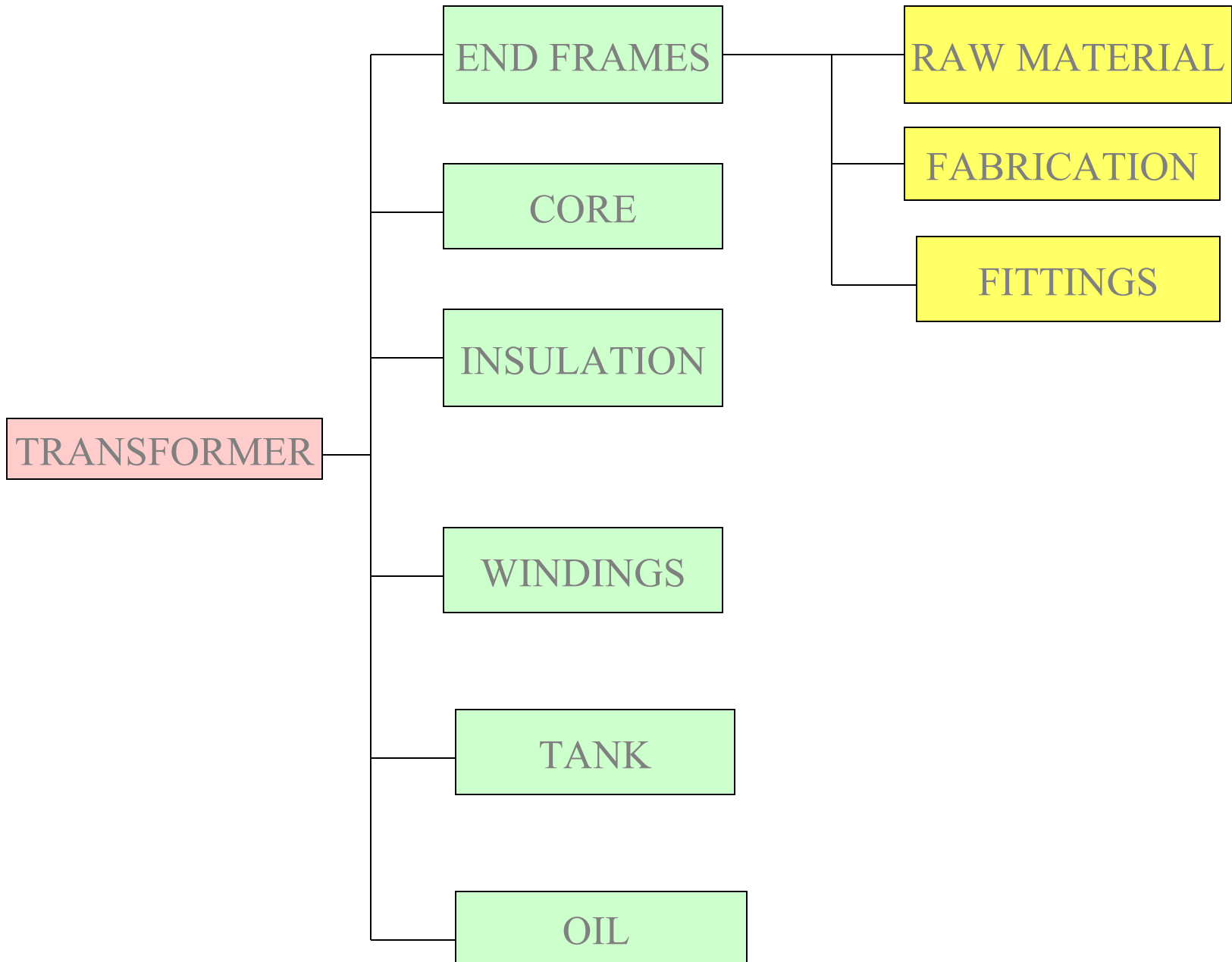
- ☹ **Old age failures: These are results of –**
 - **Ageing of insulation system**
 - **Wear & tear**

DEFECT ELIMINATION METHODS

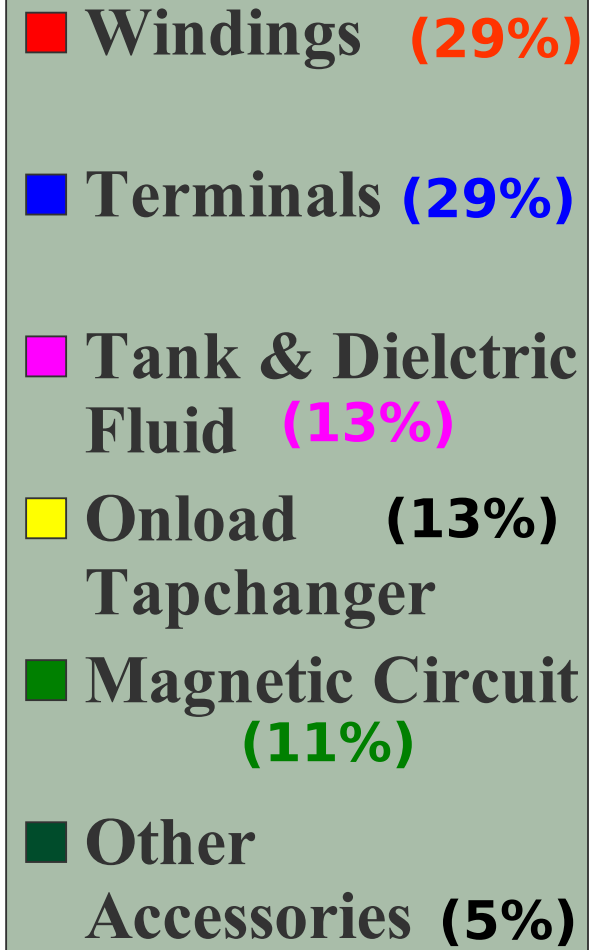
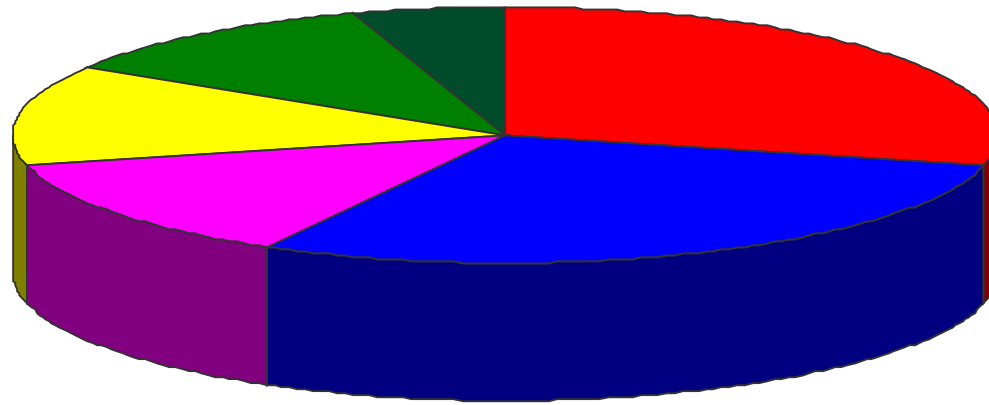
- FMEA
- FTA

MAJOR ASSEMBLIES

COMPONENT ELEMENT



COMPONENTS CAUSING FAILURE IN SERVICE



MAIN FACTORS CAUSING STRESSES IN THE WINDING

Electrical

- * Over-voltages**
- * Part winding resonance**
- * Partial Discharge**
- * Arcing**
- * Magnetizing in-rush current**
- * Over-fluxing**

MAIN FACTORS CAUSING STRESS

(continued)

- **Mechanical**
 - * **Core Vibration**
 - * **Force due to Short Circuit or Faults**
- **Thermal**
 - * **Winding Temperature**
 - * **Core loss**
 - * **Core Shorting**
 - * **Malfunctioning of Cooling System**
 - * **Hot Spot (Local overheat)**
 - * **Arcing**

DIAGNOSTIC TOOLS FOR TRANSFORMERS

- **Hot Spot Temperature**
- **Tan Delta and Capacitance**
- **Insulation Resistance**
- **Moisture and Polarization Index**
- **Partial Discharge Detection**
- **Frequency Response Analysis**

DIAGNOSTIC TOOLS FOR TRANSFORMERS ... (continued)

- **Dissolved Gas Analysis (DGA)**
- **Degree of Polymerization**
- **Furfural in Oil**
- **Particles/fibers in Oil**

Challenges in Transformer Design & Manufacturing

- **Structures design (tank etc.)**
 - **To be designed for: Lifting & Jacking**
Full or partial vacuum
Internal Pressure
Seismic Load
 - **Tests conducted: Leakage test**
Vacuum test
Radiography (if specified)
DPT on load bearing items

Challenges in Transformer Design & Manufacturing

- **Short-circuit withstand capability**
 - **Adequate radial supports**
 - **Use of pre-compressed press-board to minimize shrinkage in service**
 - **Proper stabilization of coils**
 - **Use of glued conductors**
 - **Springs or hydraulic dampers if required**

Challenges in Transformer Design & Manufacturing

Stray losses :

- **Stray losses due to linkage of high magnitude of flux with magnetic materials**
- **Stray losses form a large part, more than 20% of total load losses**
- **These may cause hot spots**

Challenges in Transformer Design & Manufacturing

Stray losses control :

- **Measures for stray loss control**
 - **Use of laminated material**
 - **By breaking the magnetic path**
 - **By providing non-magnetic shield**
 - **By providing parallel low reluctance magnetic path**

Challenges in Transformer Design & Manufacturing

High Voltage stresses

- **Design of Insulation system to ensure withstand capability for**
 - **Lightning Impulse and Switching Surges.**
 - **Long duration high voltage system disturbances**
 - **Internal Partial Discharges**

Challenges in Transformer Design & Manufacturing

➤ This is done by -

- **Choosing type of windings**
- **Calculation/plotting of impulse / switching surges and long duration voltage stress distribution**
- **Provision of adequate major and minor insulation by using angle rings, moulded components etc.**
- **Corona shielding where required**

Reactors

- **Series Reactors**
 - For limiting fault currents
- **Smoothing Reactors**
 - For filtration of harmonics
- **Shunt Reactors**
 - For capacitive VARs compensation.

Reactors

- **Series Reactors:**
 - ❖ **Used for limiting fault currents**
 - ❖ **Connected in series with generators or feeders and transmission lines.**
 - ❖ **Capability for short-time high currents**
 - ❖ **They should have linear magnetic characteristics under fault conditions.**
 - ❖ **They are designed to withstand mechanical and thermal effects of short circuits.**
 - ❖ **They have fully insulated windings since both ends should be able to withstand the lightning impulse voltages.**

Reactors

- **Smoothing Reactors:**
 - ❖ For filtration of harmonics
 - ❖ Dry type or oil filled
- **Shunt Reactors:**
 - ❖ Used for capacitive VARs compensation.
 - ❖ Should have constant impedance upto 1.3 times rated voltage

Inductance of a Coil

- Inductance of a coil is calculated by the formula –
$$\text{Inductance} = K \times \text{Mean dia of coil} \times \text{Square of number of turns.}$$
- Factor K depends on the physical dimensions of the coil –
 - Coil height
 - Radial height

General considerations/characteristics

- The reactor should have linear characteristics
- Ability to withstand short circuit
- Fully insulated windings in case of Series Reactors
- Capability for short-time high currents
- Shunt reactors:
 - Single or three phase unit: Large rated reactors sometimes poses problems in testing. To over come this, 3 single phase units are most suitable. Further, in the case of bank, zero sequence impedance is equal to positive sequence impedance.
 - Requirement of zero sequence impedance is dependent on system considerations. If this is 90 to 100% of positive phase impedance, coreless design with magnetically shielded 5-limbed gapped core reactor is most suitable. If this value is not very important or a value of about 50 to 60%, 3-limbe gapped core reactor may be used.

- Gapped core reactor: To achieve high impedance of reactor in a core type construction, gaps having suitable size are inserted in the magnetic circuit. The required effective length of the magnetic shield is mainly dependent on the dimension of the distributed gaps in the iron core and is largely dependent on the winding height. The magnetic field of the gapped core is controlled by means of gaps. Compared with magnetically shielded coreless reactors, gapped core reactors can be operated at higher flux density, the selection of which is dependent upon the requirement of linear characteristic. Conventional type, involute disc type and radially arranged moulded types are normally employed to make the core elements. In modern reactors, moulded type radial core sections moulded in epoxy resin to prevent movement between individual laminations are commonly used. The radial laminations prevent fringing flux from entering flat surfaces of core steel, which would result in eddy current overheating and hot spots

Constructional features

- Oil immersed
- Dry type
- Coreless
- Gapped core
- With or without non-magnetic shields
- With or without magnetic shields

Reactor Construction

- **Coreless Construction:**
 - In a coreless reactor, there is no magnetic material inside the coil
- **Gapped Construction:**
 - To achieve high impedance of reactor in a core type construction, gaps having suitable size are inserted in the magnetic circuit.
 - Core can be conventional or involute disc type or radially arranged moulded type.



Thank you