SGB STARKSTROM

SMIT TRANSFORMERS

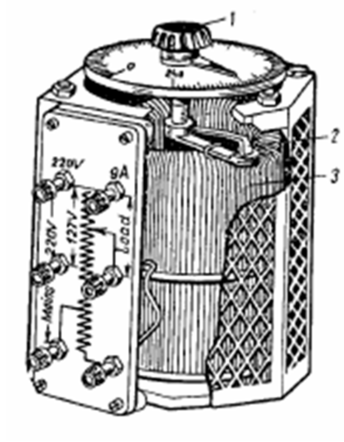
Partners in Power

Special Designs Auto-Transformers

Sanjay Y. Patel

Linda E. Peer

Introduction to Autotransformers



Auxiliary device for fine voltage adjustments

Starting induction motors (Korndorffer)

Large capacity networks

Advantages of Auto-transformers

"The KEY is kVA transformation"

- **Lower weight (lower cost)**
- **Lower losses (higher efficiency)**
- **Better regulation as lower impedance**
- **Smaller exciting current as lower core weight**
- **Smaller overall size**

Calculating an Auto-Transformer

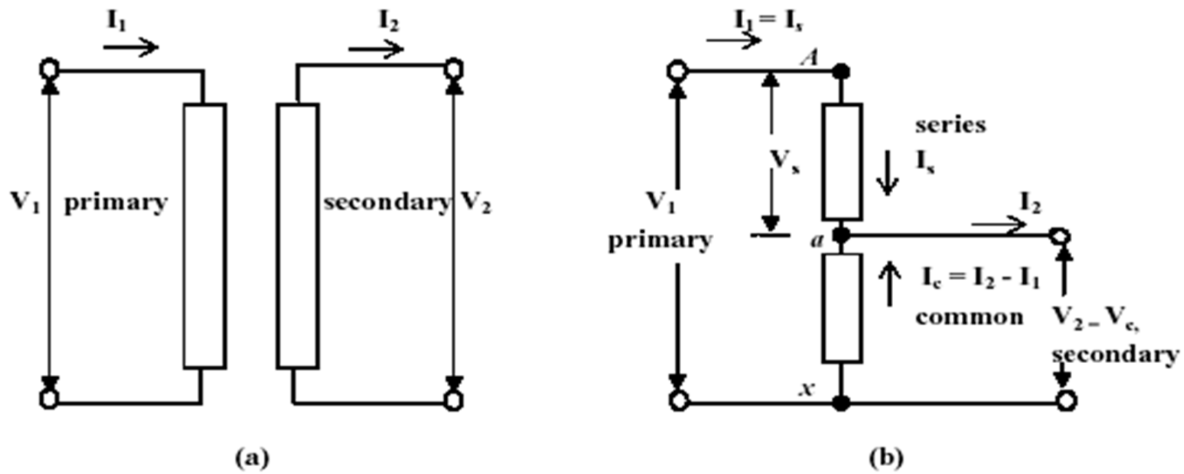


FIGURE 1. single-pahse schematic of:
(a) 2-winding transformers, (b) step-down auto-transformer

Summarized mathematically:

- Total (Thru, Name Plate) kVA "P_{NP}" = $V_1 * I_1 \approx V_2 * I_2$
- Electromagnetic (Equivalent, Design) kVA "P_{eq}" = $V_s * I_s \approx V_c * I_c$
  Since; $V_s = V_1 - V_2$, and $I_s = I_1$
  Therefore; $P_{eq} = (V_1 - V_2) * I_1$
- The co-ratio/auto fraction "α" = $P_{eq} / P_{NP} = 1 – V_2 / V_1$
- Electrical (Conductive, Transferred) kVA "P_e" = $P_{NP} - P_{eq} = P_{NP} * (1- \alpha)$

Example kVA Calculation

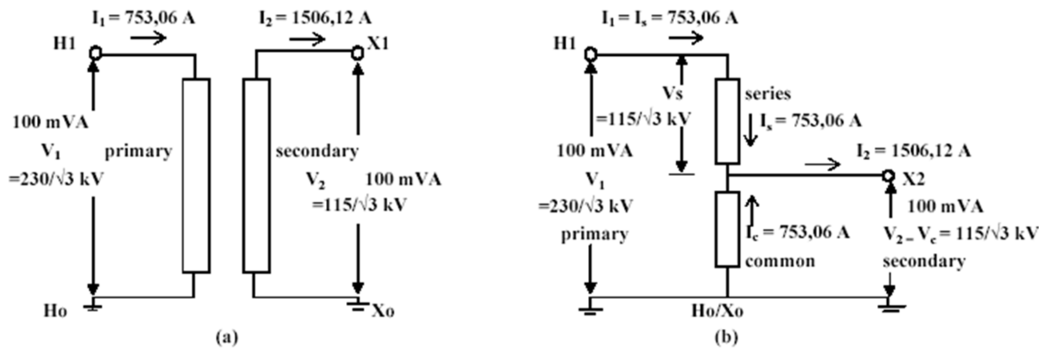


FIGURE 2. single-pahse 100 mVA, 230/115 kV
(a) 2-winding transformers, (b) step-down auto-transformer

<u>2-winding transformer</u>

Primary winding = 753.06 * 230/√3
= 100,000 kVA

Secondary winding = 1506.12 * 115/√3
= 100,000 kVA

Total kVA "P_{NP}" = (100,000+100,000)/2
= 100,000 kVA

<u>Auto-transformer</u>

Transformation ratio = 230/115 = 2

The co-ratio α = 1-1/2 = .5

Equivalent kVA "P_{eq}" = 100,000 * .5
= 50,000 kVA

<u>OR calculated as:</u>

Series winding (primary) = 753.06 * 115/ √3
= 50,000 kVA

Common winding (secondary) = 753.06 * 115/ √3
= 50,000 kVA

Electromagnetic "P_{eq}" = (50,000+50,000)/2
= 50,000 kVA

Electrical kVA "Pe" = 100,000 *(1-1/2)
- 50,000 kVA

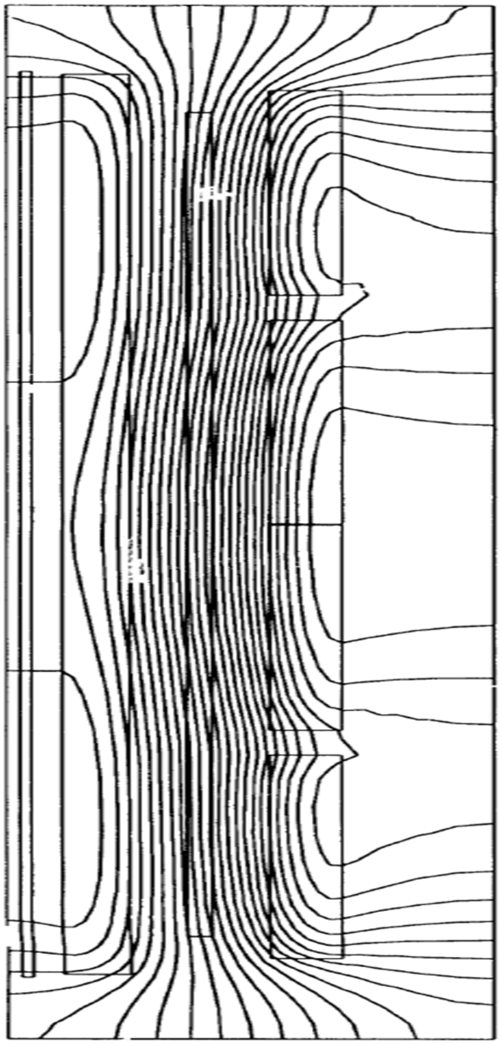
Total kVA "P_{NP}" = P_{eq} + Pe
= 100,000 kVA

Disadvantages of Auto-transformers

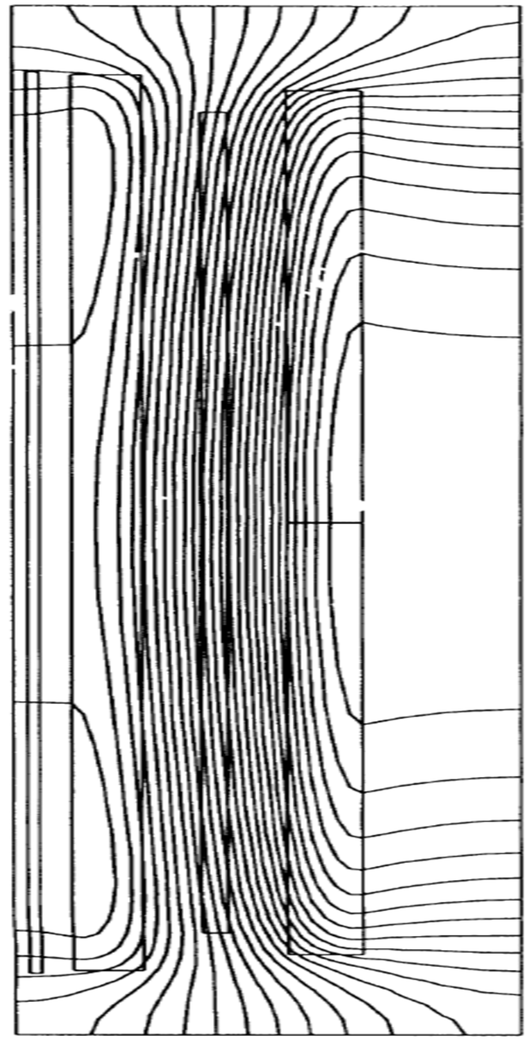
"Nothing comes for free"

- **Effective percentage impedance**
  - Short circuit stresses
- **Electrical connection**
  - Equipment in LV may be under high potential
  - Impulse problem (over-voltage) is more severe
  - Voltage regulation

PROBLEM: Short circuit stresses
Black and white FEA program magnetic field plots

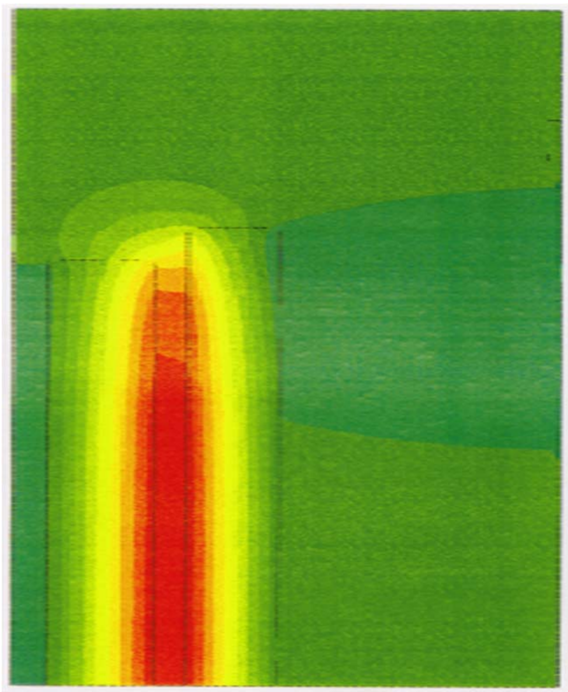


Auto-transformer with taps in main body of series winding

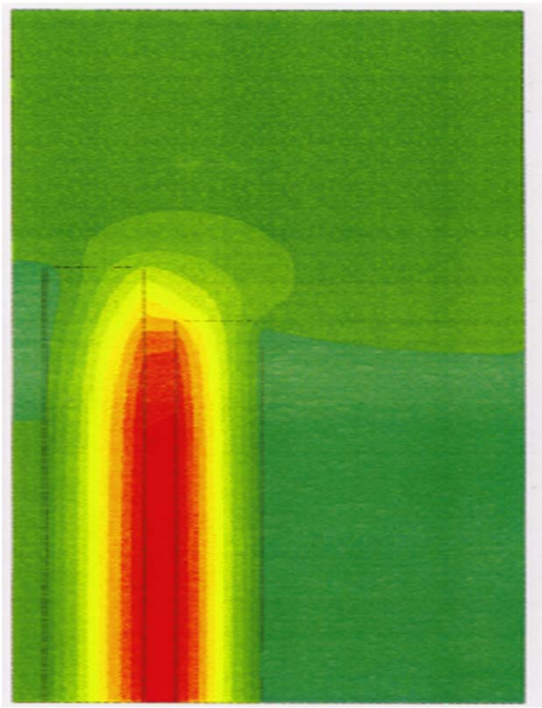


Auto-transformer with taps in a separate tap winding

ANALYSIS: Minimize short circuit stress
Using color FEA program



LV shorter than HV

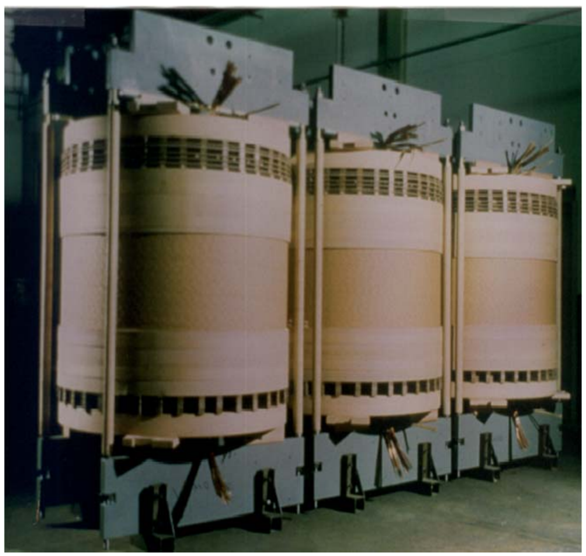


LV taller than HV

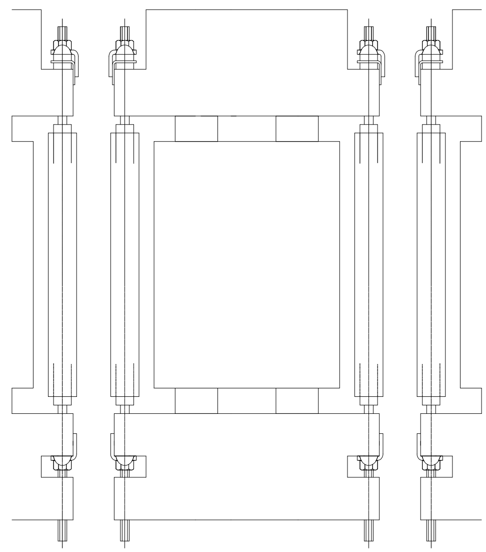
Leakage Magnetic Field Plot

SOLUTION: Techniques to avoid mechanical stresses

- Restrict / minimize axial insulation in the windings
- Use of epoxy bonded CTC as winding conductor
- Maximum radial support on winding turns

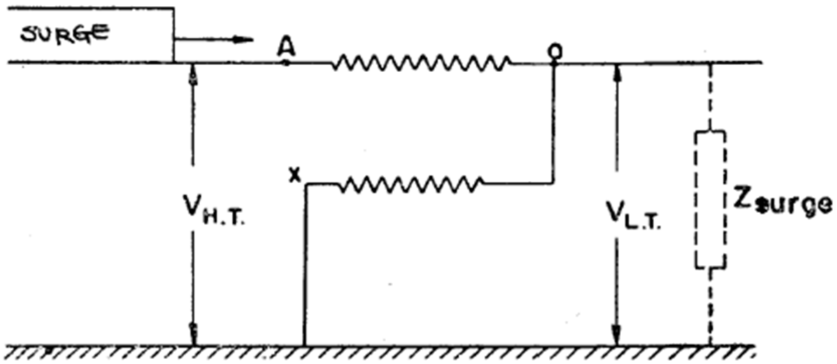


SMIT windings with individual phase clamping

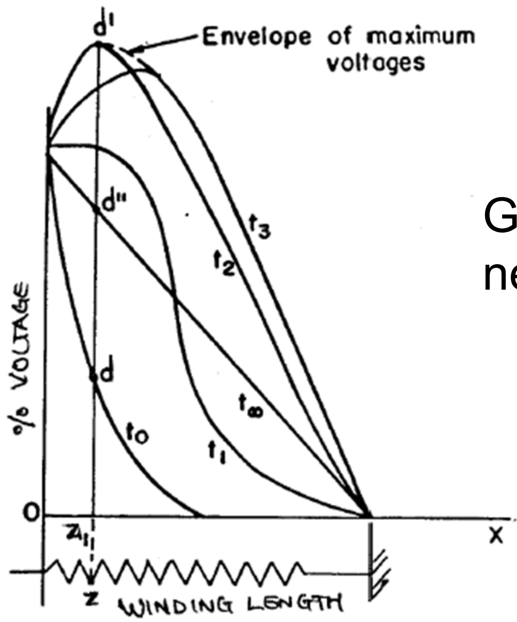


Uniform radial support

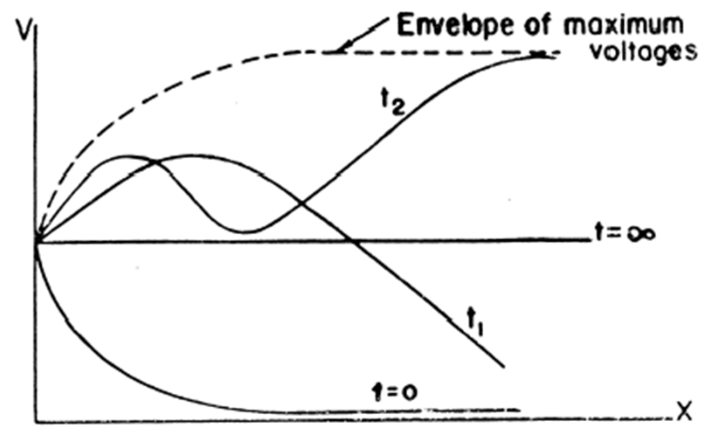
PROBLEM: Over-voltage



Auto-transformer with grounded neutral (surge from HV side)



Grounded neutral



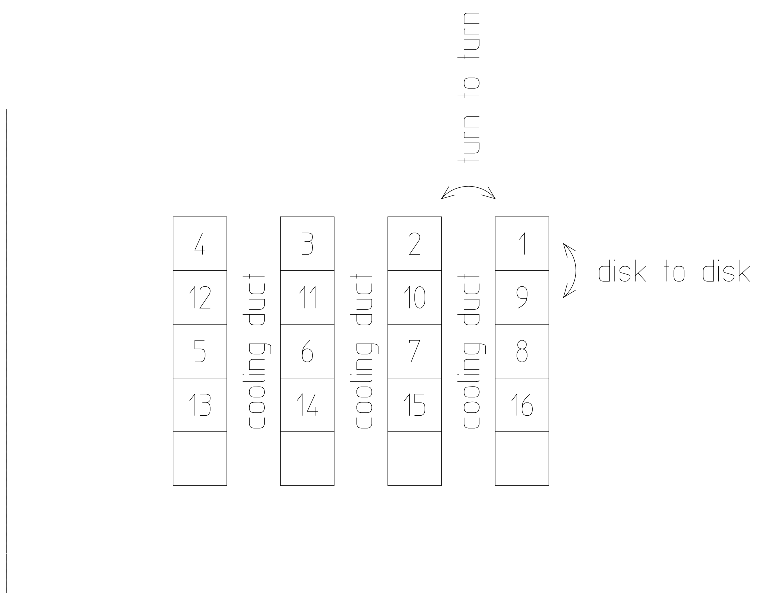
Isolated neutral

Voltage distribution along a transformer winding

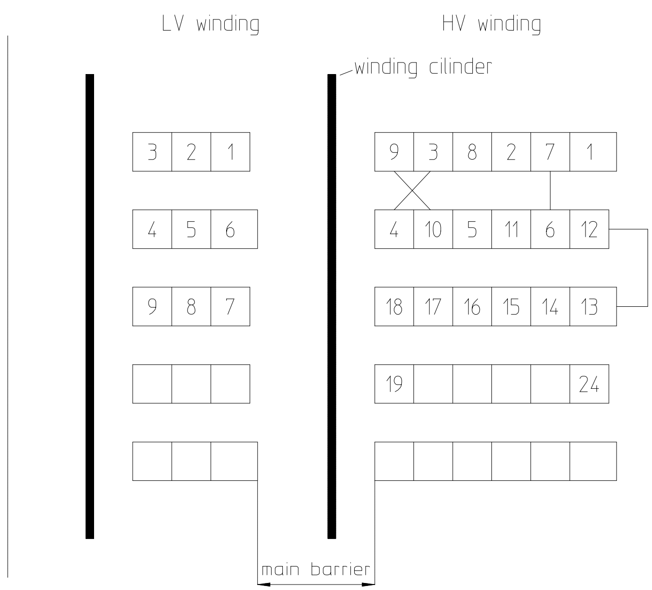
SOLUTION: Internal protection

- Proper selection of winding design

Interleaved HV disk windings



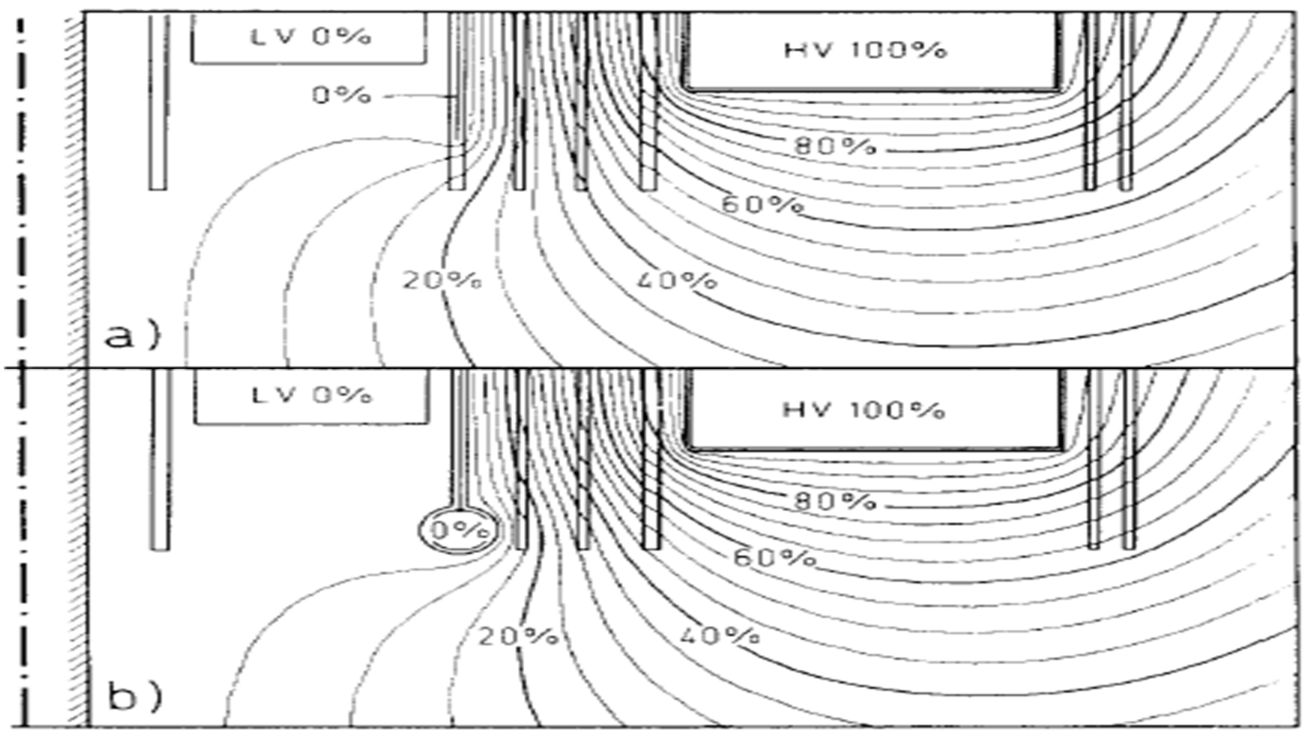
SMIT design



Other conventional designs

SOLUTION: Internal protection

- Intensive study of behavior of active parts to voltage surges
  - FEA program for electrostatic field plots

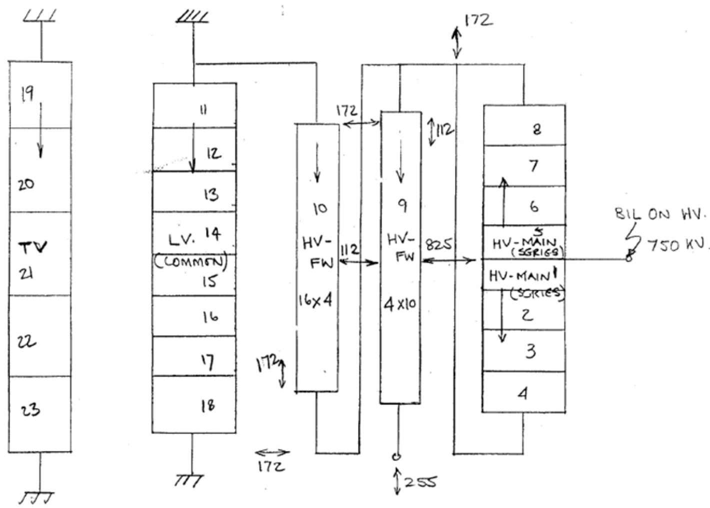


Shielding cylinder with sharp-ended strips

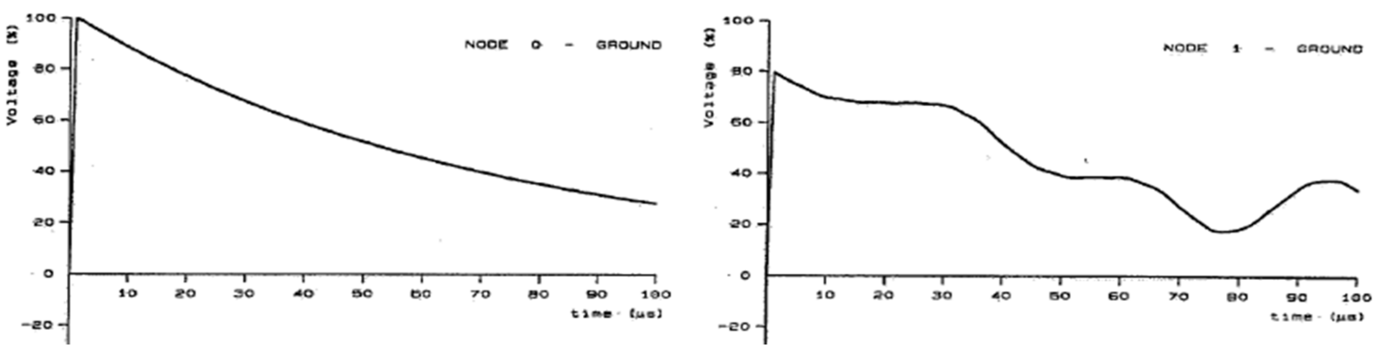
Shielding ring for relieving strip ends

SOLUTION: Internal protection

- Impulse programs re: inductance-capacitance circuit of core and coils



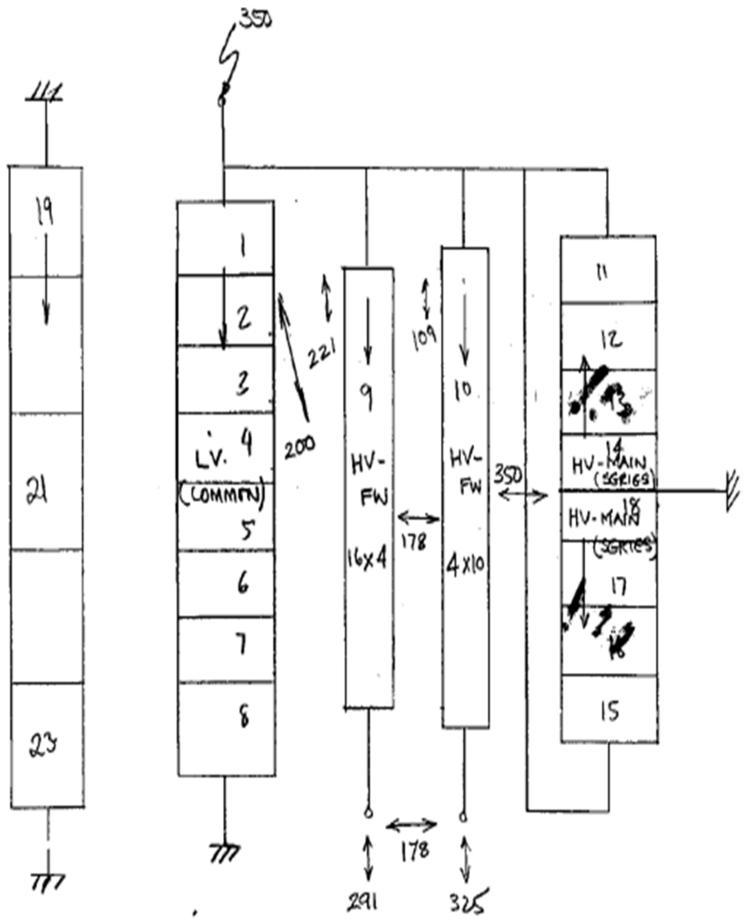
Transformer model



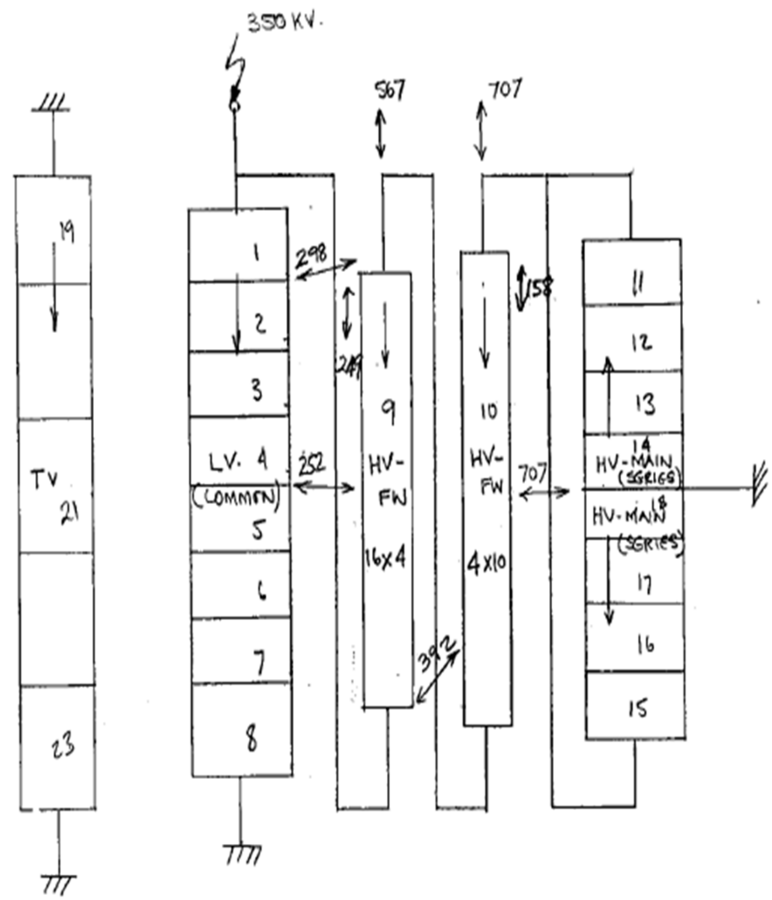
FW-Impulse response at various nodes

SOLUTION: Internal protection

Impulse on LV (common) winding



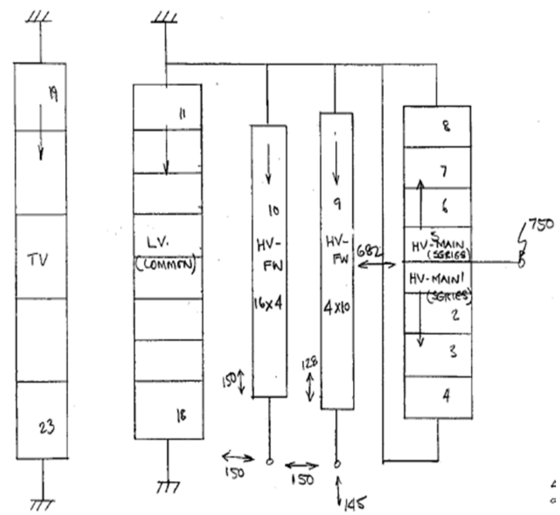
Minimum turns in HV



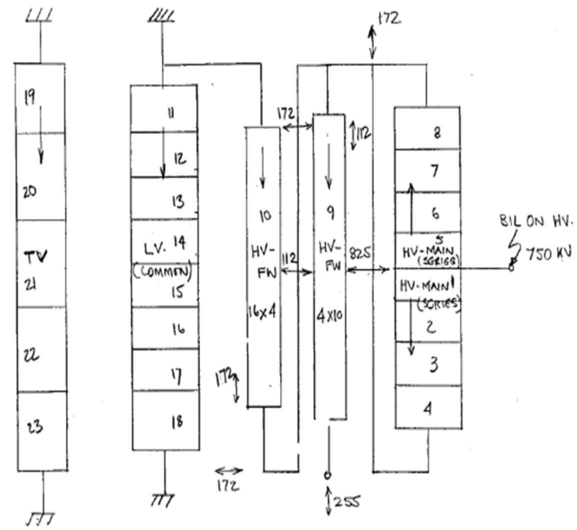
Maximum turns in HV

SOLUTION: Internal protection

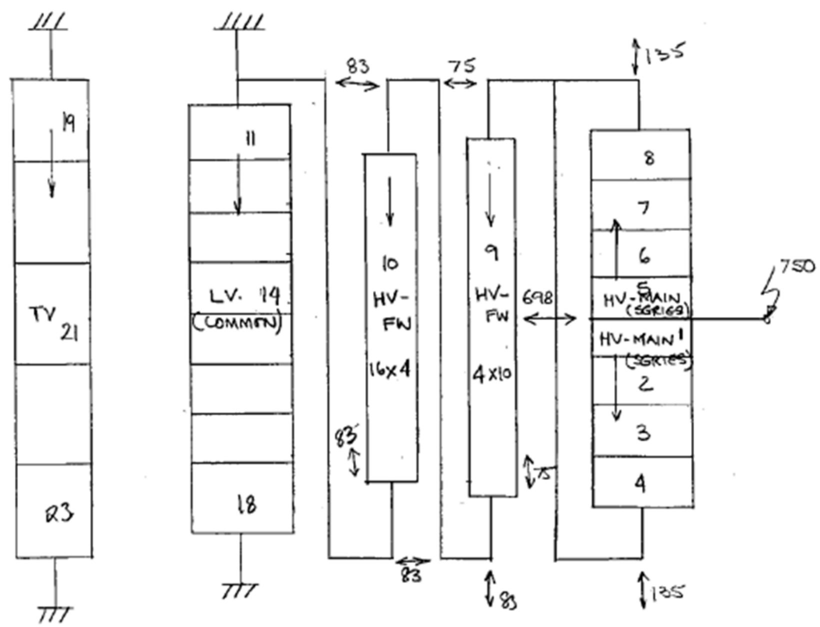
Impulse on HV (series) winding



HV (series) winding at minimum turns



HV (series) winding at minimum effective turns



HV (series) winding at minimum effective turns

SOLUTION: External protection

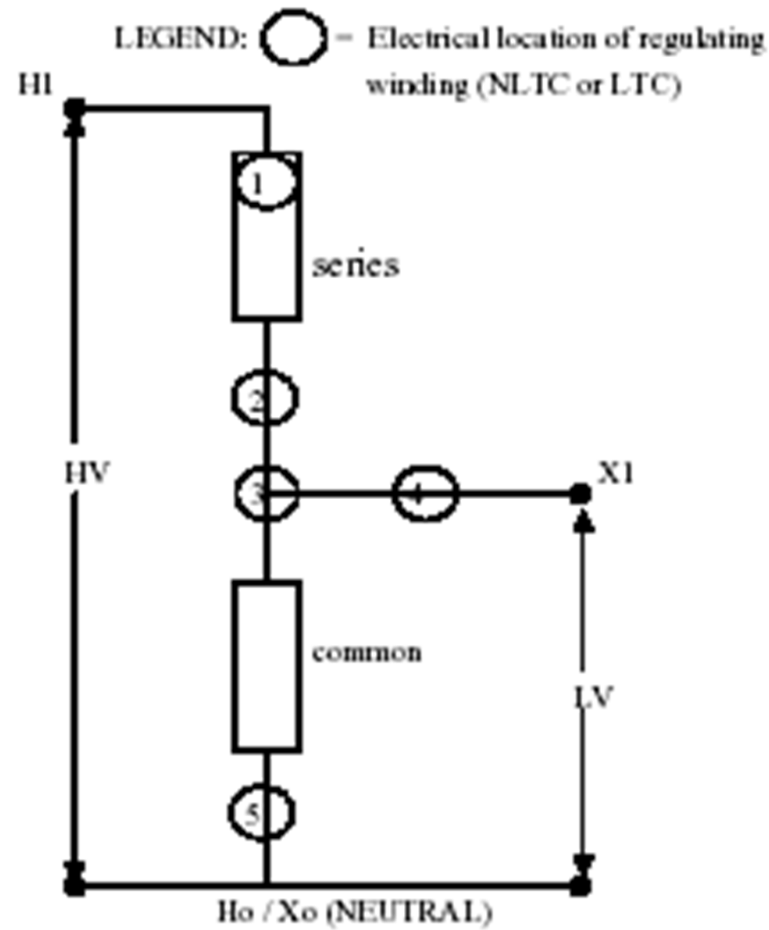
- Correct choice of distribution lines to avoid districts immune to heavy thunderstorms
- Use of overhead ground wires
- Proper insulation coordination with use of lightening arrestor installed at substation

Voltage Regulation and Its Influence on Impedance

- Tap changers (NLTC or LTC)
  - Influence on design and impedance profile
    - Electrical location
      - Constant flux design
      - Variable flux design
    - Geometrical location
  - Increase in equivalent size of auto-transformer
  - Increase in cost of auto-transformer

Electrical Location

- Main body of series winding
  - Common for NLTC application or (rare cases) LTC when number of step required is high to regulate HV voltage (constant flux design)
- Separate winding, electrically connected to series winding (above the auto point)
  - Common for NLTC and/or LTC application to regulate HV or LV voltage (in the case of LV voltage, variable flux design)
- Fork of auto-transformer connection
  - Common for NLTC and/or LTC application to regulate LV voltage (constant flux design)
- Line end of LV voltage
  - Common for LTC application or (rare cases) NLTC to regulate the LC voltage (constant flux design)
- Neutral end of auto-transformer connection
  - Common for NLTC or LTC application to regulate either HV or LV voltage (variable flux design)



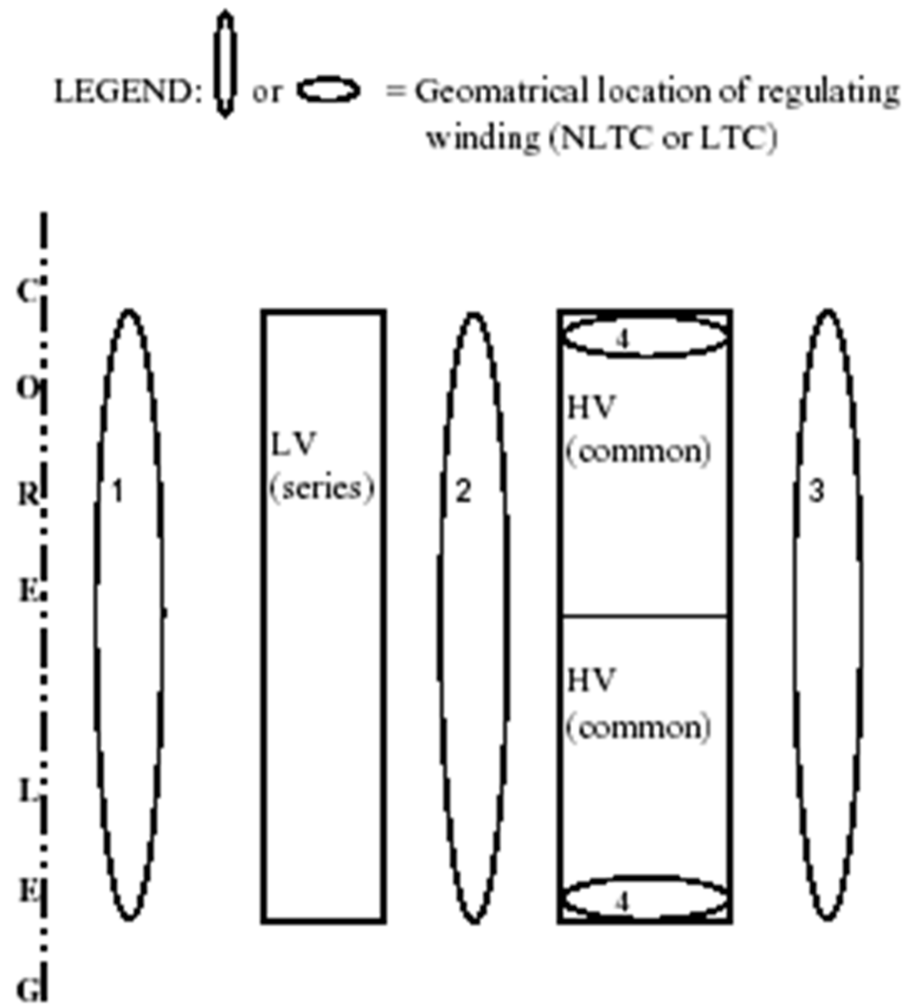
Electrical Location

The following aspects should be considered to select the correct electrical location:

- NLTC or LTC Equipment
  - Voltage to ground
  - Voltage across tap winding
  - Current through contacts
  - Step voltage
- Regulating winding
  - Number of turns per tap (critical for winding design type)
  - Protection (such as zinc-oxides)

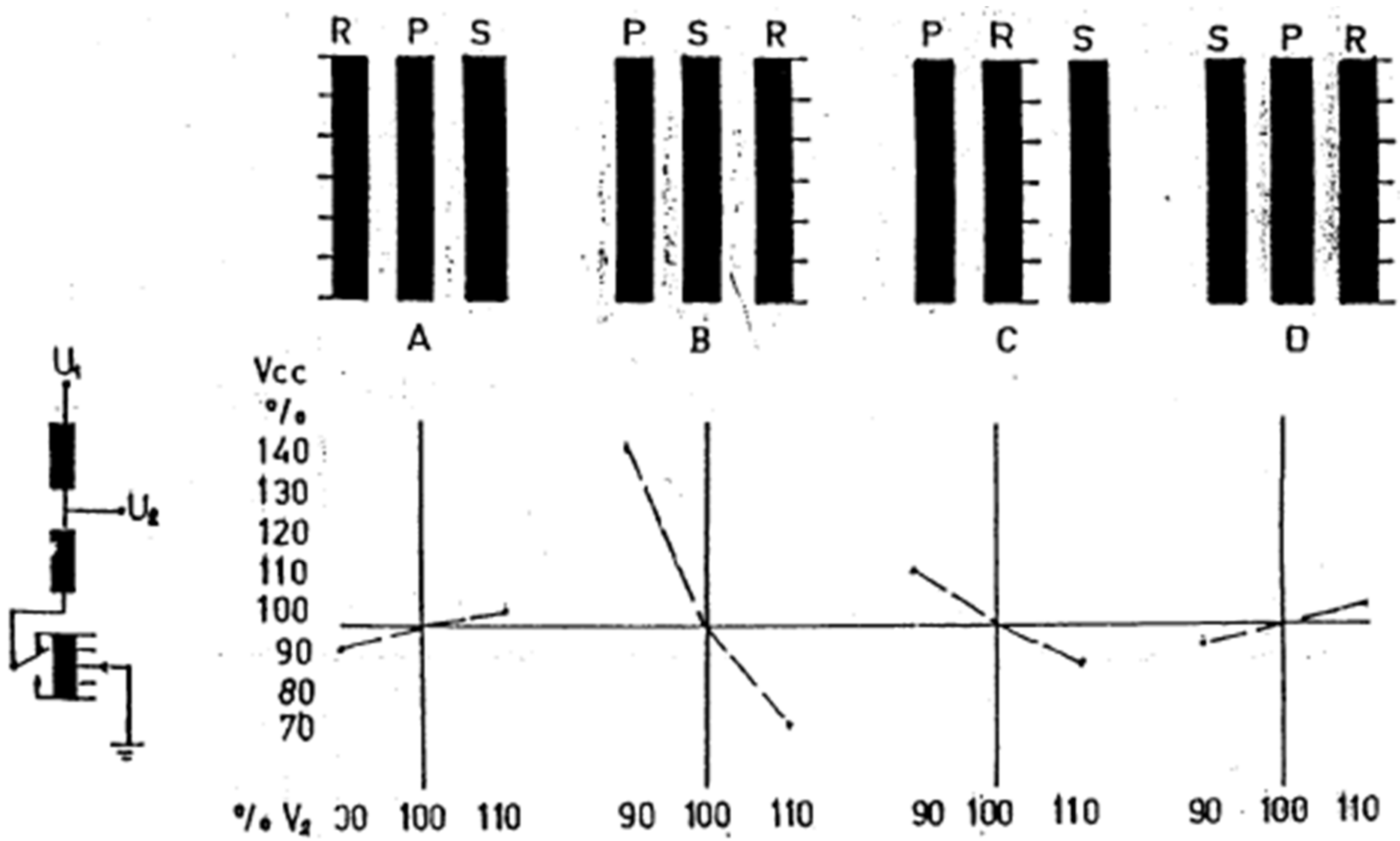
Geometrical Location

- Innermost diameter
  - Common for regulating winding connected to neutral end or line end of LV voltage
- Between series and common windings
  - Common for regulating winding connected to series winding or line end of the LV voltage
- Outermost diameter
  - Common for regulating winding connected to series winding
- Main body of the series winding
  - Common for regulating winding connected to series winding



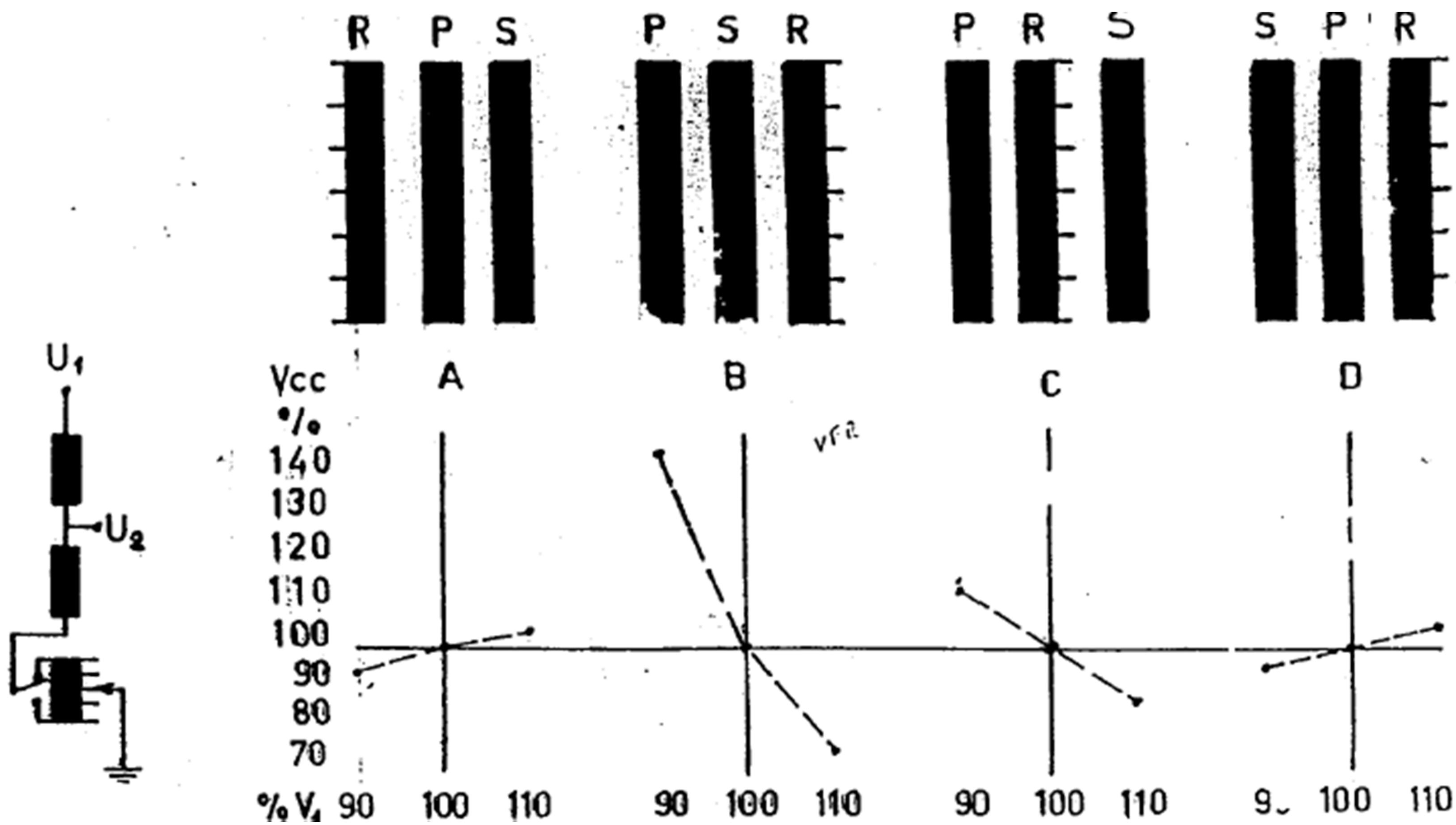
Geometrical Location

Example: LV side voltage regulation with regulating winding electrically connected to neutral end of Auto-transformer (ratio 400 / 135 kV ± 10%)



Geometrical Location

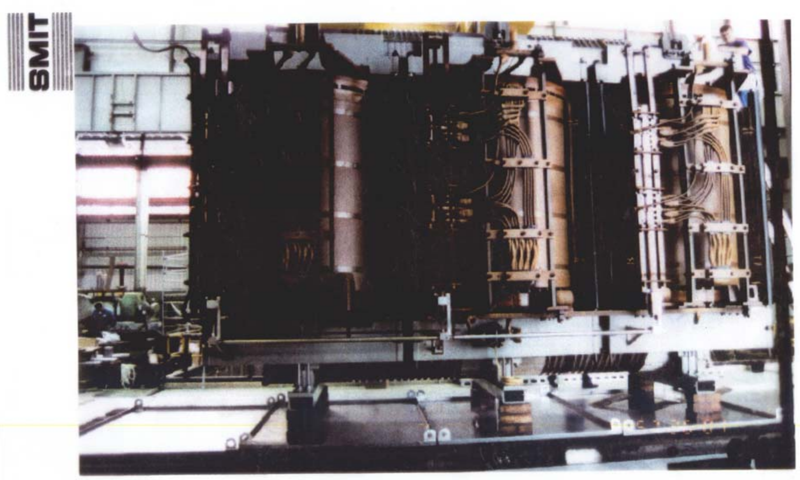
Example: HV side voltage regulation with regulating winding electrically connected to neutral end of Auto-transformer (ratio 400 / 135 kV ± 10%)



Geometrical Location

The following aspects should be considered to select the correct geometrical location:

- Regulating winding design
  - Voltage between windings
  - Impedance variation over the tap range
  - Difficulties in parallel operation
  - Lead layout design



DETC leads

LTC leads

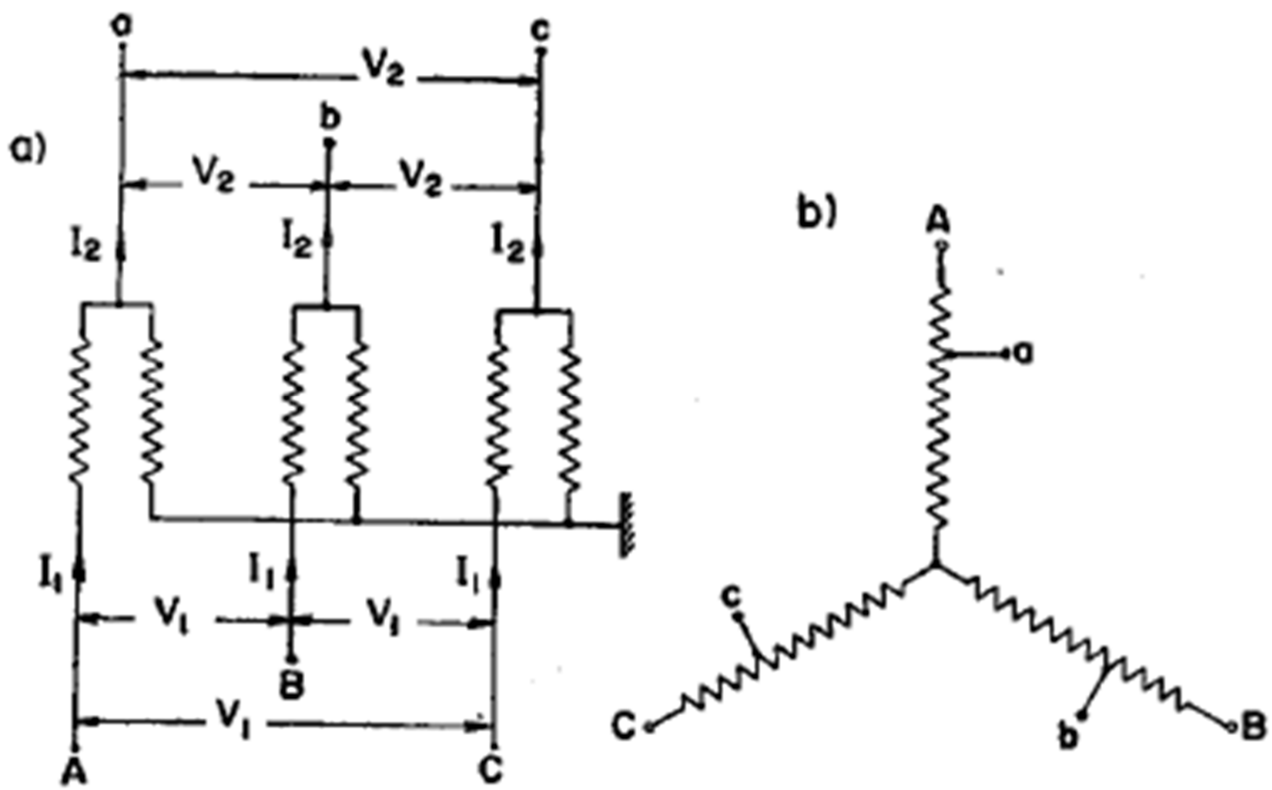
Comparison:

Regulating winding in neutral end (variable flux design) and line end (constant flux design)

	LTC IN COMMON WINDING NEUTRAL REACTOR TYPE SWITCH	LTC IN LV LINE W/O SERIES TRANS RESISTOR TYPE SWITCH
SERIES TRANSFORMER TO COMPENSATE TV	IF TV IS REQUIRED AND IT IS TO SUPPLY LEVEL VOLTAGE	NONE
CORE WEIGHT	HEAVIER	LIGHTER
COIL WEIGHT	USUALLY HEAVIER	USUALLY LIGHTER
VOLTS PER TURN	VARIES	STEADY
RATIO ERROR	VARIES	NONE
NORMAL COPPER LOSS	USUALLY HIGHER	USUALLY LOWER
CORE LOSS OVER TAP RANGE	VARIES	STEADY
% IMPEDANCE OVER TAP RANGE	VARIES	ALMOST LEVEL
NOISE OVER TAP RANGE	VARIES	STEADY
MAXIMUN TOTAL LOSS	HIGHER	LOWER
RADIATORS	USUALLY MORE	USUALLY LESS
FANS	USUALLY MORE	USUALLY LESS
PREVENTIVE AUTO	USUALLY REQUIRED	NONE IF RESISTOR
TAPPED WINDING INSULATION	LESS	MORE
TAPPED WINDING BIL	LOWER	HIGHER
TAPPED WINDING AMPS	LOWER	HIGHER
TAPPED LEAD CONSTRUCTION	EASIER	HARDER
LTC SWITCH	SMALLER & LESS EXPENSIVE	LARGER & COSTLIER
OPTIMAL TOTAL OWNING COST	HV TO LV RATIO > 2	HV TO LV RATIO < 2

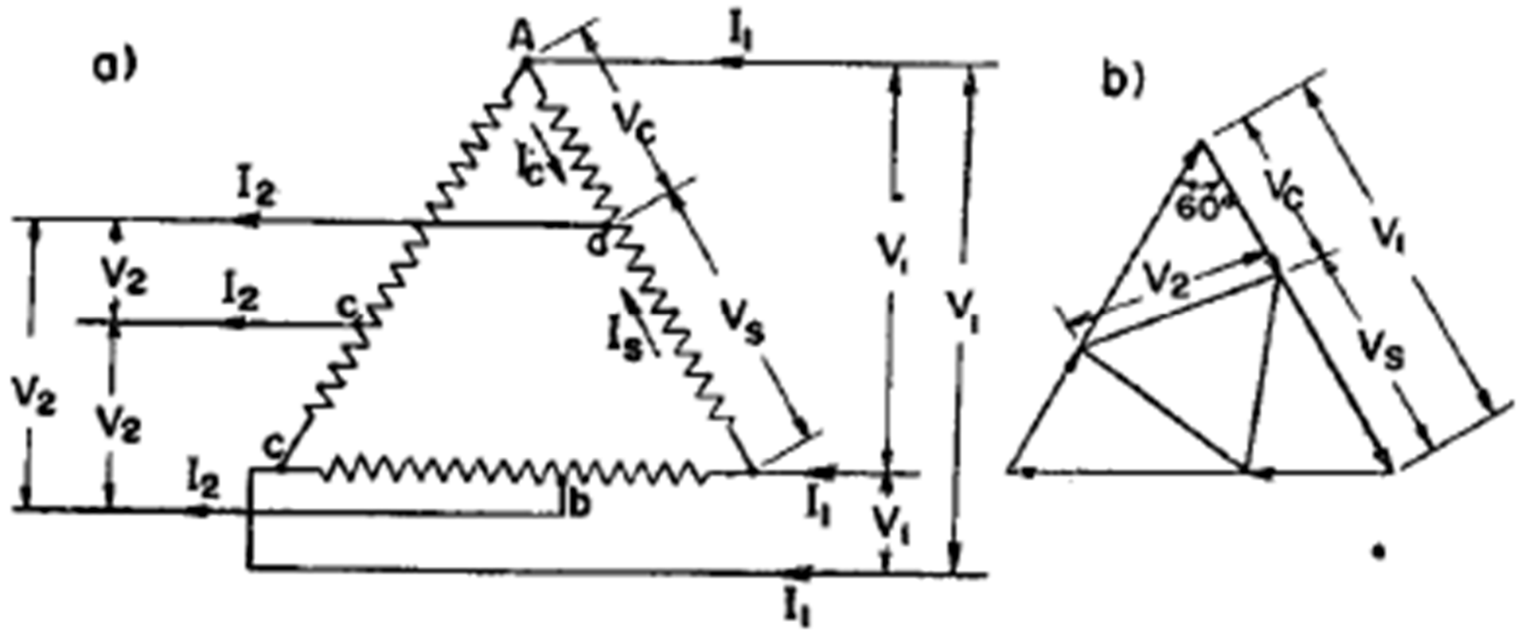
Three-Phase Auto-Transformer Connections

- Y-connection
  - Simplest and most economical connection



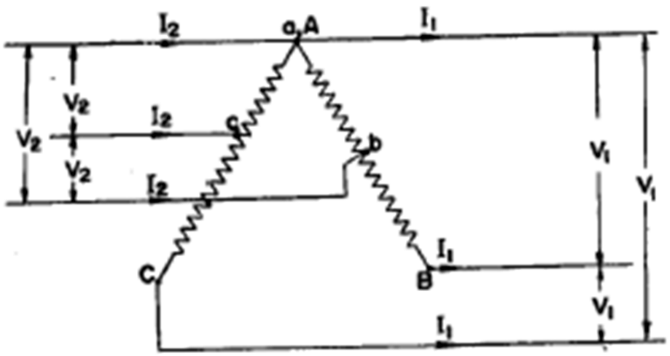
Three-Phase Auto-Transformer Connections

- Delta connection
  - Rarely used as its co-ratio is larger than Y-connection by approx. 1.16 – 1.73 times
  - May be valuable in case of a Phase Shifting Transformer

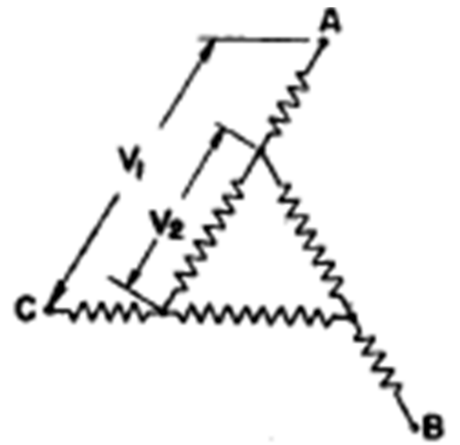


Three-Phase Auto-Transformer Connections

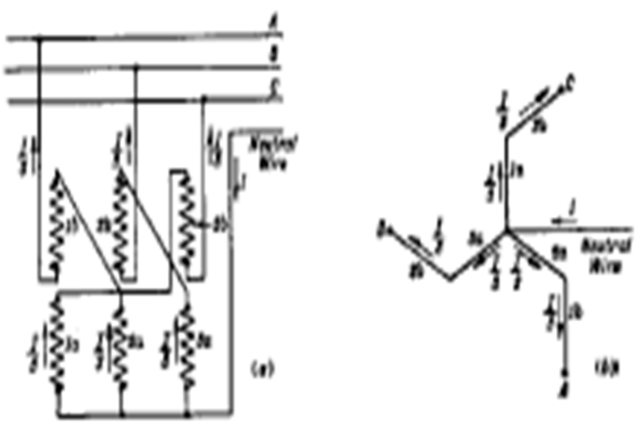
- Other connections



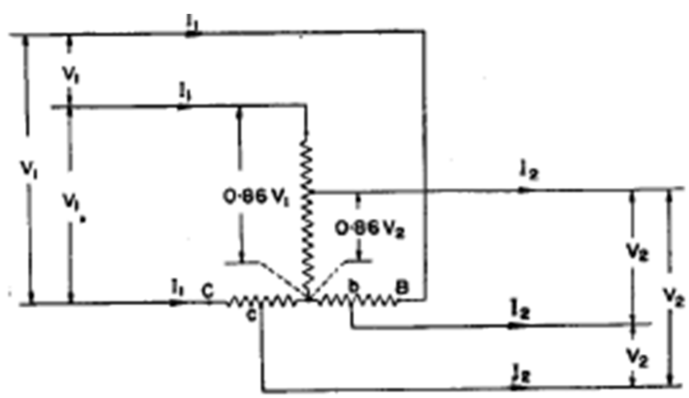
Open Delta-connection



Extended Delta-connection



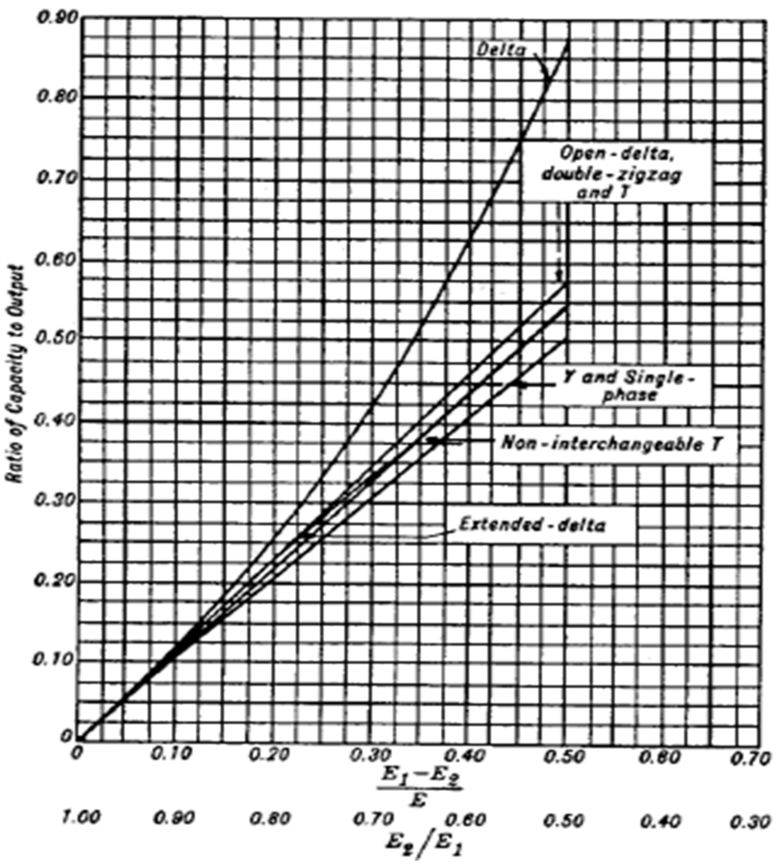
Single zigzag connection



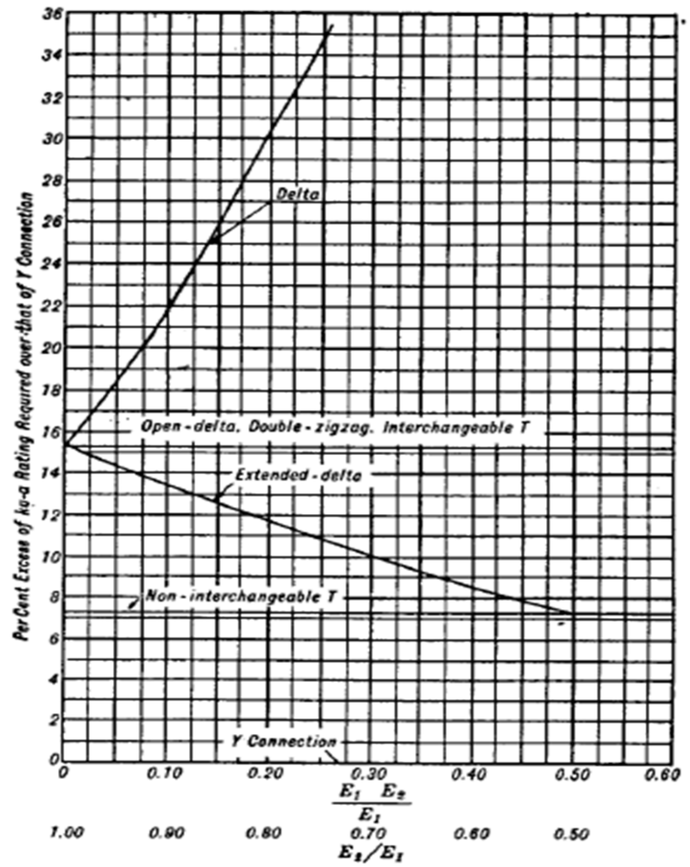
T-connection

Three-Phase Auto-Transformer Connections

Other Connections Comparison Graphs



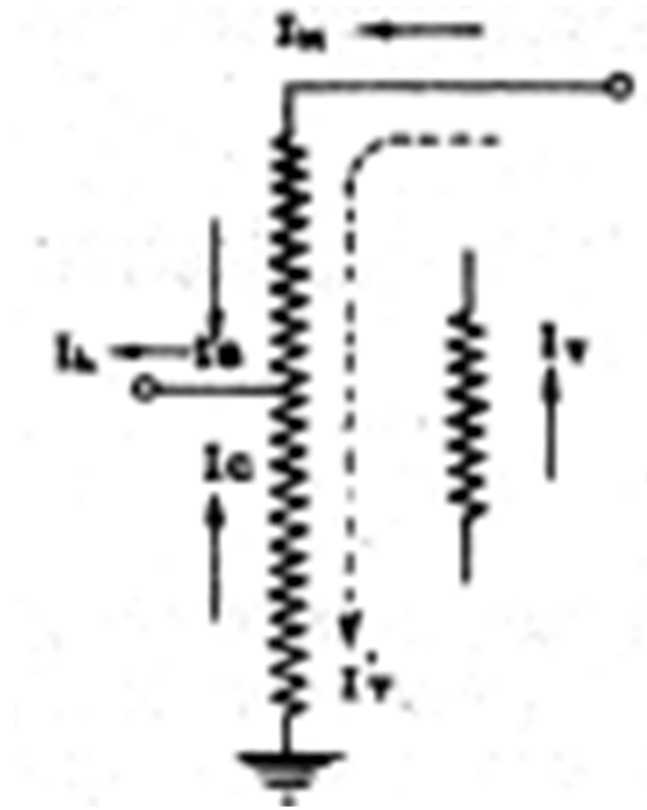
Ratio of capacity to output of various other connections



Capacity required by various other connections compared with Y-connection

Delta-Connected Tertiary Winding

- Supply auxiliary load
- Suppress third harmonic currents and voltages in lines
- Stabilize neutral point of fundamental frequency voltages
- Reduce zero sequence impedance of transformer to zero sequence currents flowing during fault conditions and unbalanced loading conditions
- Power factor improvement by connecting synchronous condensers to tertiary winding



Current division in step-down mode for auto-transformer with tertiary load

Testing of Auto-Transformers

- Tests the same as a 2-winding transformer
- Impulse test
- Heat-run test

Conclusion

“Auto-Transformers should be used every time when applicable”

- Considerable cost savings
  - Lower total losses
  - Lower size
  - Better regulation
  - Lower exciting current
- Disadvantages have solid solutions
  - Use of FEA programs to study impulse and short circuit behavior can realize optimum design
- Limited impedance variation
  - Tap changers
    - Electrical location
    - Geometrical location
- Tertiary winding omission
  - More cost savings
  - Better reliability