Transformer Design & Design Parameters

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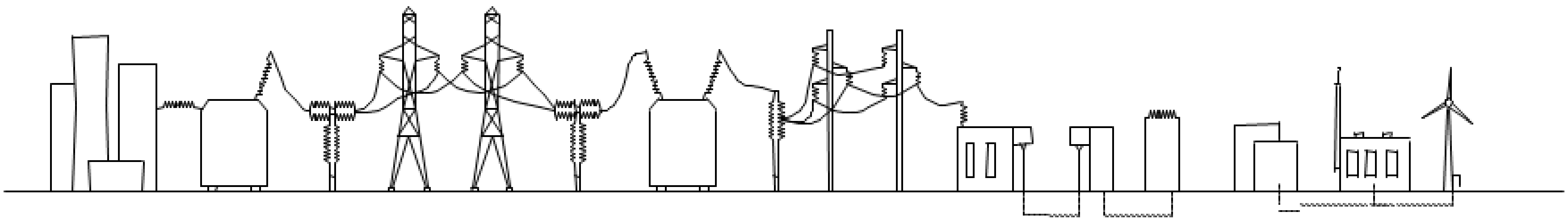
Power Transmission + Distribution



GENERATION	TRANSMISSION	SUB-TRANSMISSION	DISTRIBUTION	DISTRIBUTED POWER
115/10 or 20 kV		500/230	230/13.8	
132		345/161	161	
161		230/115	132	
230		230/132	115	
345			69	
500			34	
Generator Step-Up transformer		Auto-transformer	Step-down transformer	pads

Standards

U.S.A.

- (ANSI) IEEE Std C57.12.00-2010, standard general requirements for liquid-immersed distribution, power and regulation transformers
- ANSI C57.12.10-2010, safety requirements 230 kV and below 833/958 through 8,333/10,417 KVA, single-phase, and 750/862 through 60,000/80,000/100,000 KVA, three-phase without load tap changing; and 3,750/4,687 through 60,000/80,000/100,000 KVA with load tap changing
- (ANSI) IEEE C57.12.90-2010, standard test code for liquid-immersed distribution, power and regulating transformers and guide for short-circuit testing of distribution and power transformers
- NEMA standards publication no. TR1-2013; transformers, regulators and reactors

Canada

CAN/CSA-C88-M90(reaffirmed 2009); power transformers and reactor; electrical power systems and equipment

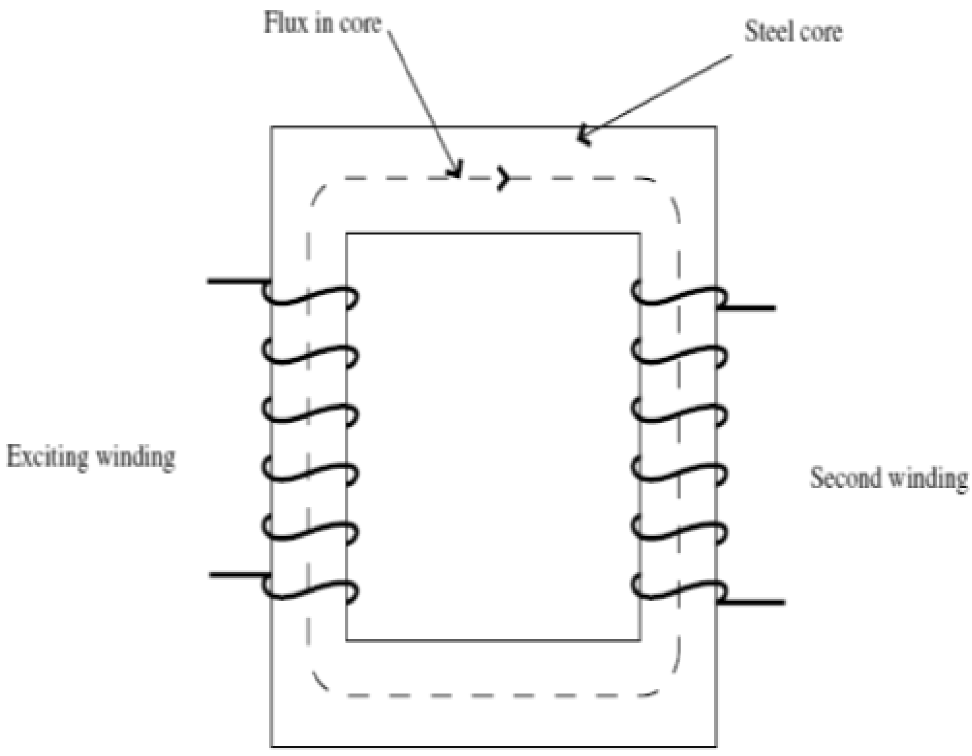
Transformer Design:

- Power rating [MVA]
- Core
- Rated voltages (HV, LV, TV)
- Insulation coordination (BIL, SIL, ac tests)
- Short-circuit Impedance, stray flux
- Short-circuit Forces
- Loss evaluation
- Temperature rise limits, Temperature limits
- Cooling, cooling method
- Sound Level
- Tap changers (DTC, LTC)

Transformer Design:

Simple Transformer

- Left coil - input (primary coil)
  - Source
  - Magnetizing current
- Right coil - output (secondary coil)
  - Load
- Magnetic circuit



Power rating [MVA]

Power rating S [MVA] for three-phase transformer is defined as:

$$S = \sqrt{3} \cdot U \cdot I$$

Where:

U - rated line voltage (primary or secondary),

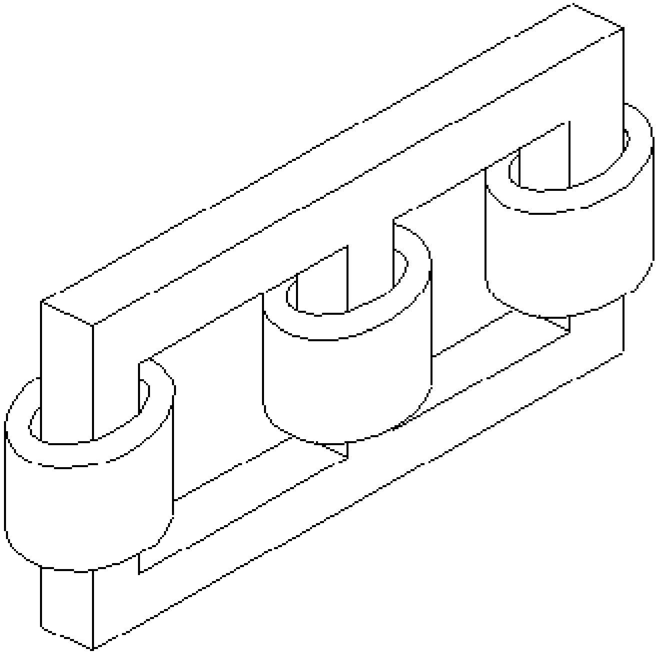
I - rated line current (primary or secondary).

Power rating [MVA]

- 30/40/50 MVA corresponding to different cooling stages, e.g. ONAN/ONAF/ONAF (OA/FA/FA), 0.6/0.8/1.0 p.u.
- 60/80/100//112 MVA for 55/65^{o}C temperature rise units; 12% increase in power rating for 65^{o}C rise from 55^{o}C rise,
- 24/12/12 MVA for three-circuit units (e.g. HV-LV1-LV2).

Core Form

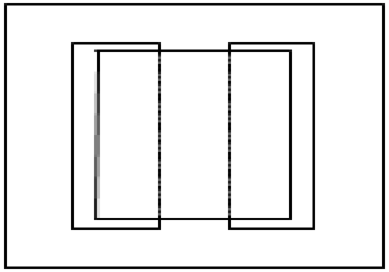
- *Concentric windings*
- *'Set' Winding Geometry*
- *Cooling options*
- *Cost consideration*
- *Shipping differences*



Transformer Design:

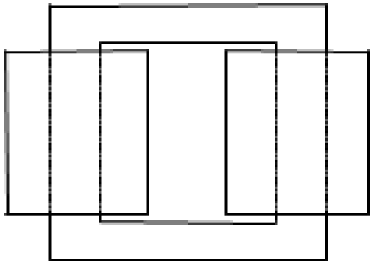
Type of Cores

Type 1



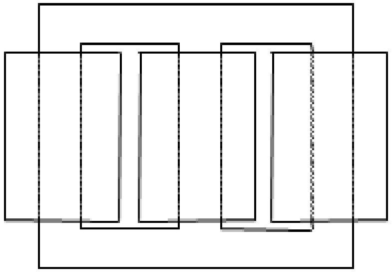
- *3 legs*
  - *1 wound leg*
  - *2 return legs*
- *legs and yokes not of equal cross section*
- *single-phase*

Type 2



- *2 legs*
  - *2 wound legs*
- *legs and yokes of equal cross section*
- *single-phase*

Type 3

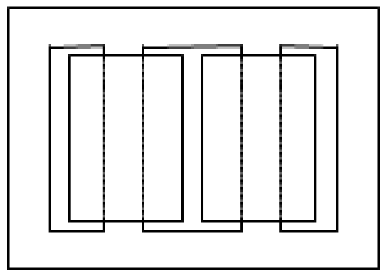


- *3 legs*
  - *3 wound legs*
- *legs and yokes of equal cross section*
- *three-phase*

Transformer Design:

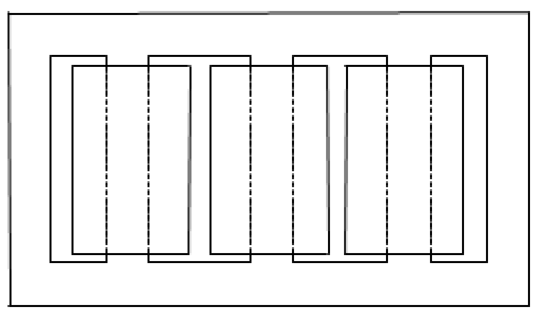
Type of Cores

Type 4



- *4 legs*
  - *2 wound legs*
  - *2 return legs*
- *legs and yokes not of equal cross section*
- *single-phase*

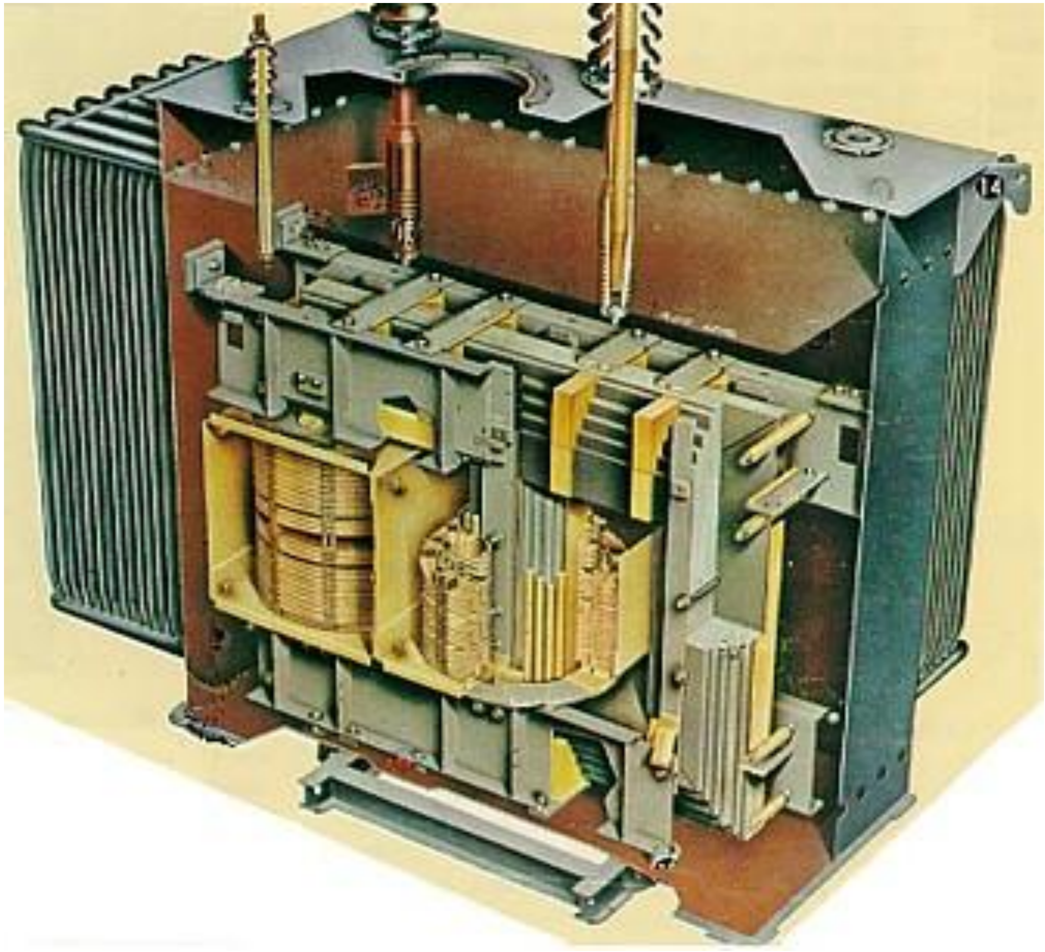
Type 5



- *5 legs*
  - *3 wound legs*
  - *2 return legs*
- *legs and yokes not of equal cross section*
- *three-phase*

Transformer Design:

Core Form Cutaway



Insulation Coordination

- Basic Insulation Level (BIL) tested with lightning impulse 1.2/50 μs (FW, CW)
- Switching Insulation Level (SIL), switching impulse 250/2500 μs
- Induced Voltage (ac)
- Applied Voltage (ac)

Transformer Design:

Insulation Coordination

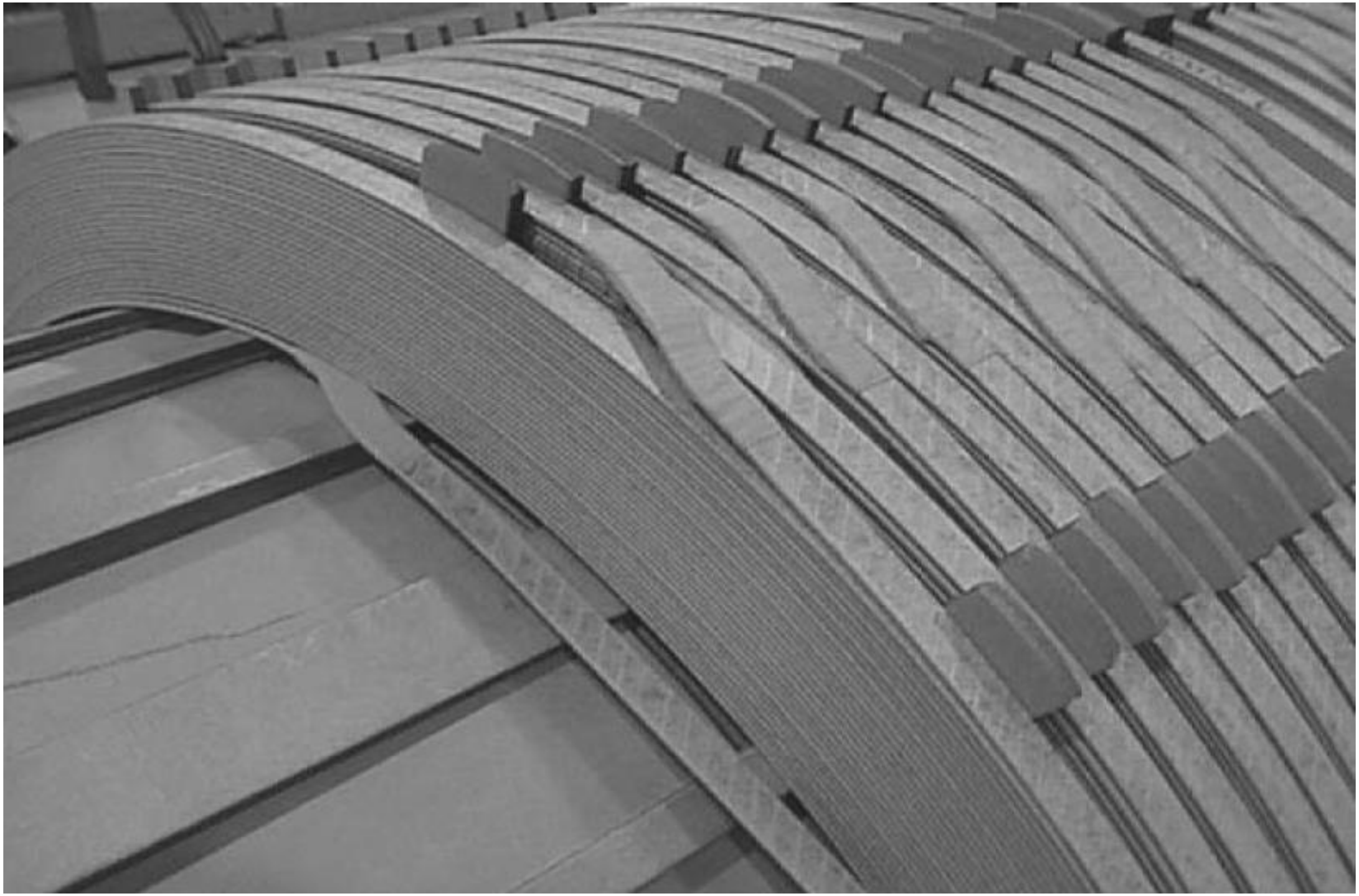
Withstand voltage	***Impact on design***
BIL (LI)	Bushings, lead structure & its clearances, winding clearances, stresses to ground, neutral point insulation
SIL	External clearances, lead clearances, phase-to-phase stresses
Induced voltage	Internal winding stresses (V/T), stresses to ground, phase-to-phase stress
Applied voltage	Stresses to ground (windings, leads)

High Voltage (HV)

- Voltage class of the unit, levels of LI and SI, are determining selection of bushings, surge arrestors, insulating structure (graded or fully insulated, internal and external clearances, use of barriers, caps and collars, stress rings, etc.)
- impulse voltage distribution dictates the winding type, main gaps, type of conductor (MW, Twin, Triple, CTC)

Manufacturing Process:

Coil Winding(Disc inner and outer Crossovers)



Low Voltage (LV)

- Low voltage generates the highest currents in transformer, determining selection of bushings, lead structure, etc.
- Stray field problems have to be addressed i.e. use of non-magnetic inserts, magnetic shunts, e.t.c,
- selection of winding type (low temperature rise - use of CTC, short-circuit withstand)

Manufacturing Process:

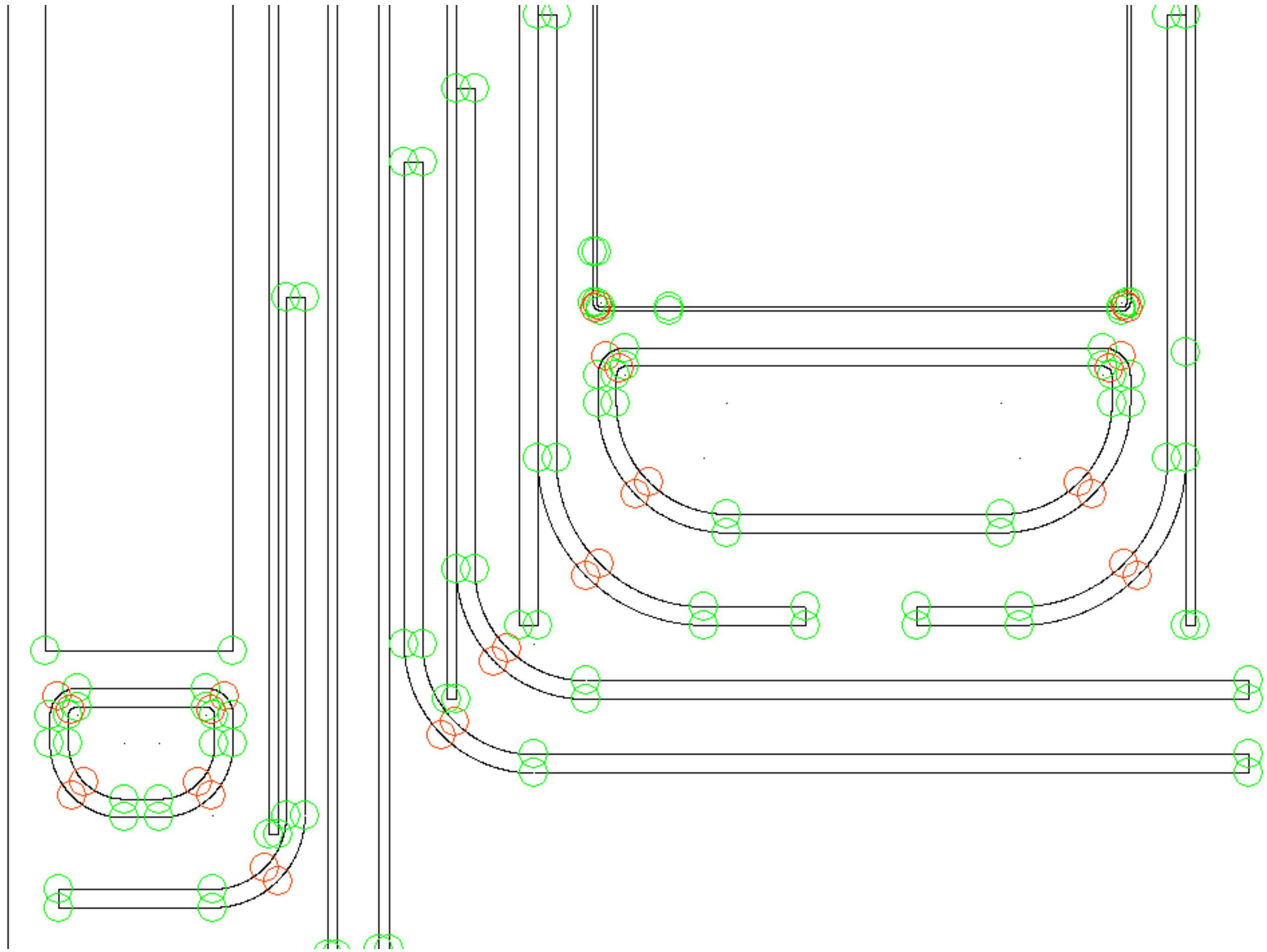
CTC - epoxy bonded, netting tape

Tertiary Voltage (TV)

TV can be brought out to supply tertiary circuit, or can be not brought out (buried).

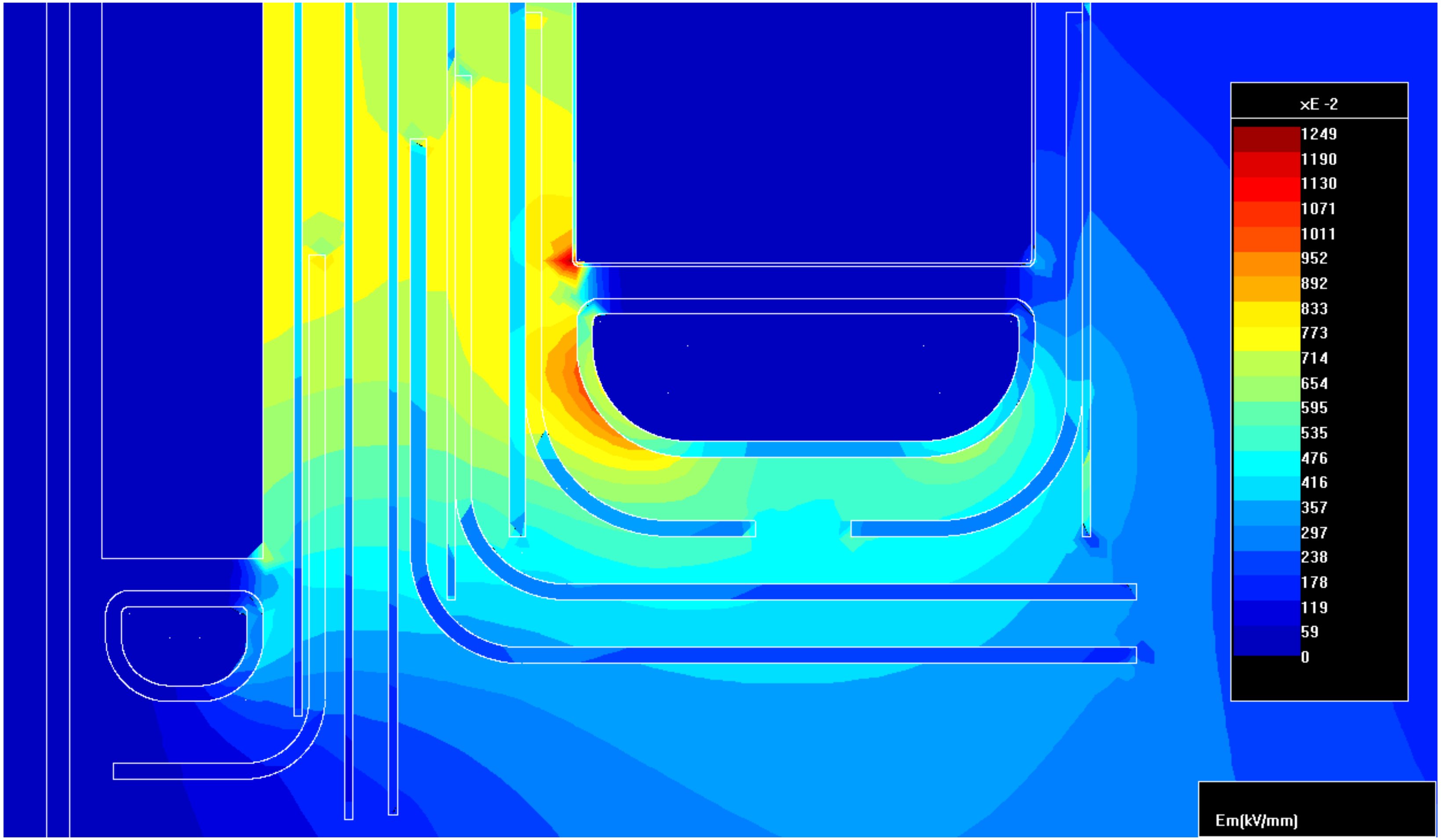
- For brought out TV design follows the rules as for LV, i.e. sizing the bushings, leads, short-circuit faults
- Tertiary voltage generated at buried TV winding has no importance for user; typically such TV winding is delta connected and provides the path for zero-sequence currents during short-circuit and suppresses third harmonic (and its multiples) currents.

Geometry of end insulation



Transformer Design:

End insulation
Electric field distribution



Short-circuit impedance

- Determines the regulation (voltage drop across transformer) under load conditions
- Limits the short circuit currents and resulting forces
- Specified by customer (can be per IEEE Std)
- Can be expressed in % of rated impedance (equal to % value of short-circuit voltage), or in [Ω] related to primary or secondary side
- In general Z=R+jX, but resistance is negligible
- %IX depends on: geometry, amp-turns, base power, frequency

Short-circuit impedance

Short-circuit reactance is calculated using the magnetic field programs (finite element, Rabins); can be estimated using simple formulas;

High value of stray reactance in design results in:

- high leakage flux, leading to high additional (eddy) losses in windings and constructional parts,
- can result in increase in the highest (hot-spot) temperature rises; use of CTC is expected (also in HV winding) - higher manufacturing cost;
- the value of voltage regulation is high
- short-circuit current are limited, forces are low.

Low value of impedance may result in large short-circuit currents, leading to high forces; the designing is difficult, more copper must be added, epoxy bonded CTC cables have to be used, more spacers are added.

Short-circuit Design

Basic theory

- Current carrying conductors in a magnetic field experience force in accordance with Fleming's left hand rule.
- Axial flux produces radial force and radial flux produces axial force
- Conductors are attracted to each other when currents are in same direction
- Conductors are pushed away from each other when currents are in opposite direction
- Force is proportional to square of current

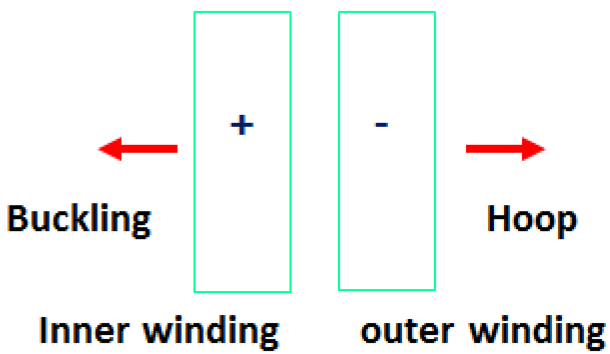
Short-circuit Design

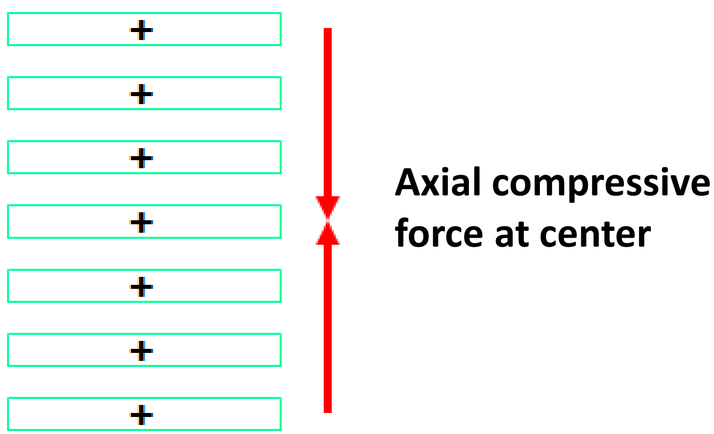
Types of forces

- Radial force due to axial flux
- Axial Compressive force due to current in same winding
- Axial force due to unbalance ampere turns in the windings (radial flux condition)

Short-circuit Design

Radial forces





Stresses due to radial forces

- Hoop stress in outer winding
- Buckling stress in inner winding

  Supported buckling and free buckling

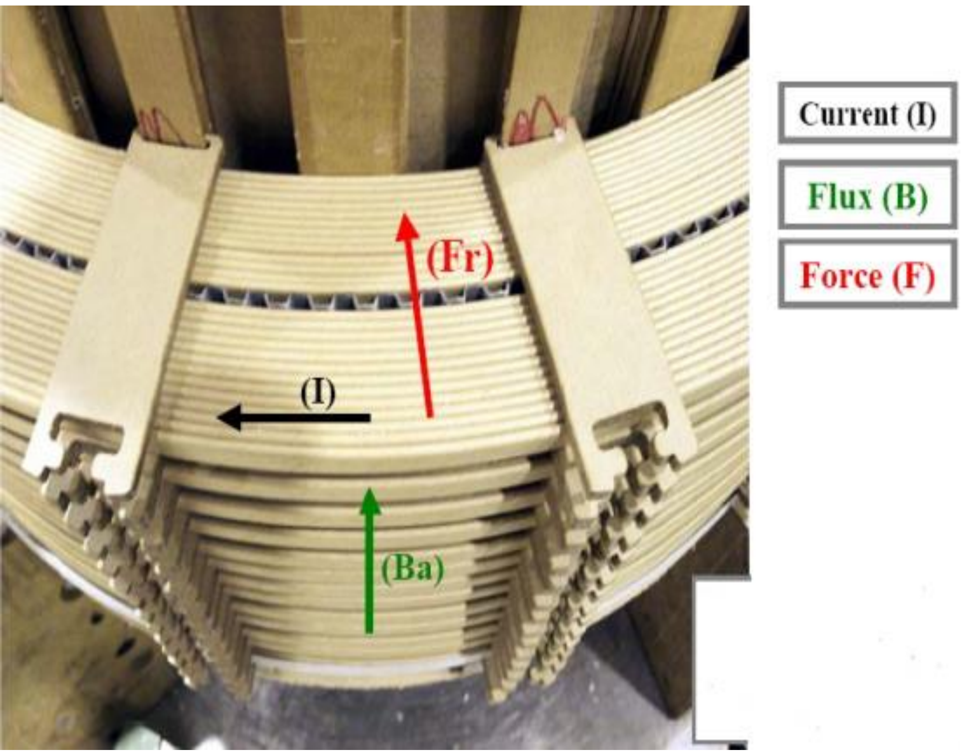
Stresses due to axial forces

- Compressive stress on key spacers
- Tilting of conductors
- Axial bending between key spacers

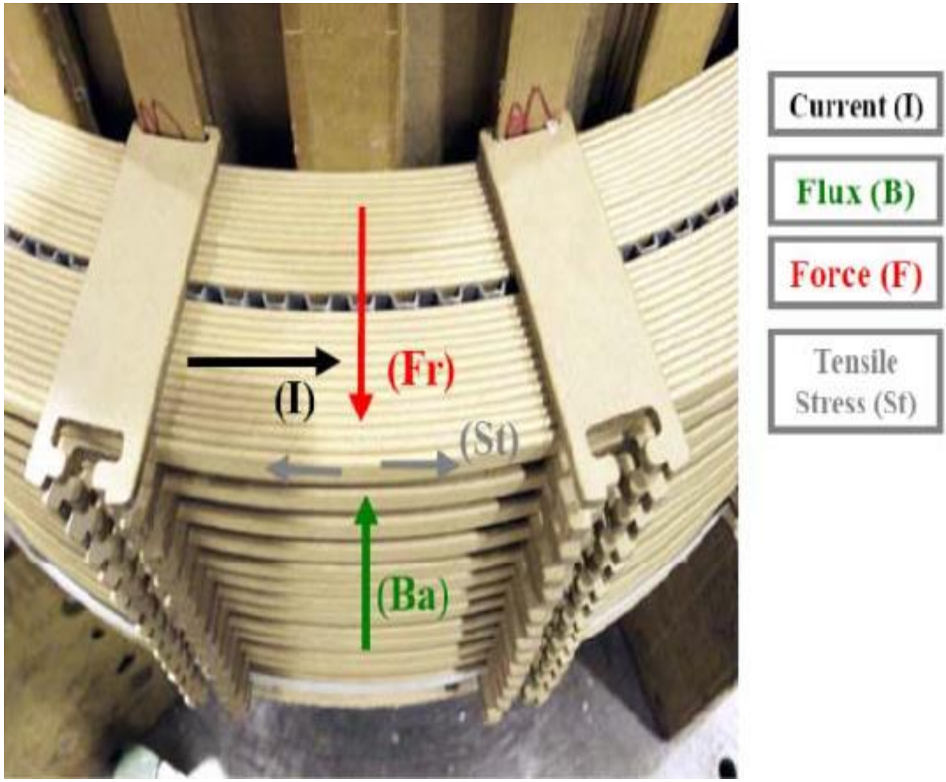
Transformer Design:

Radial Forces

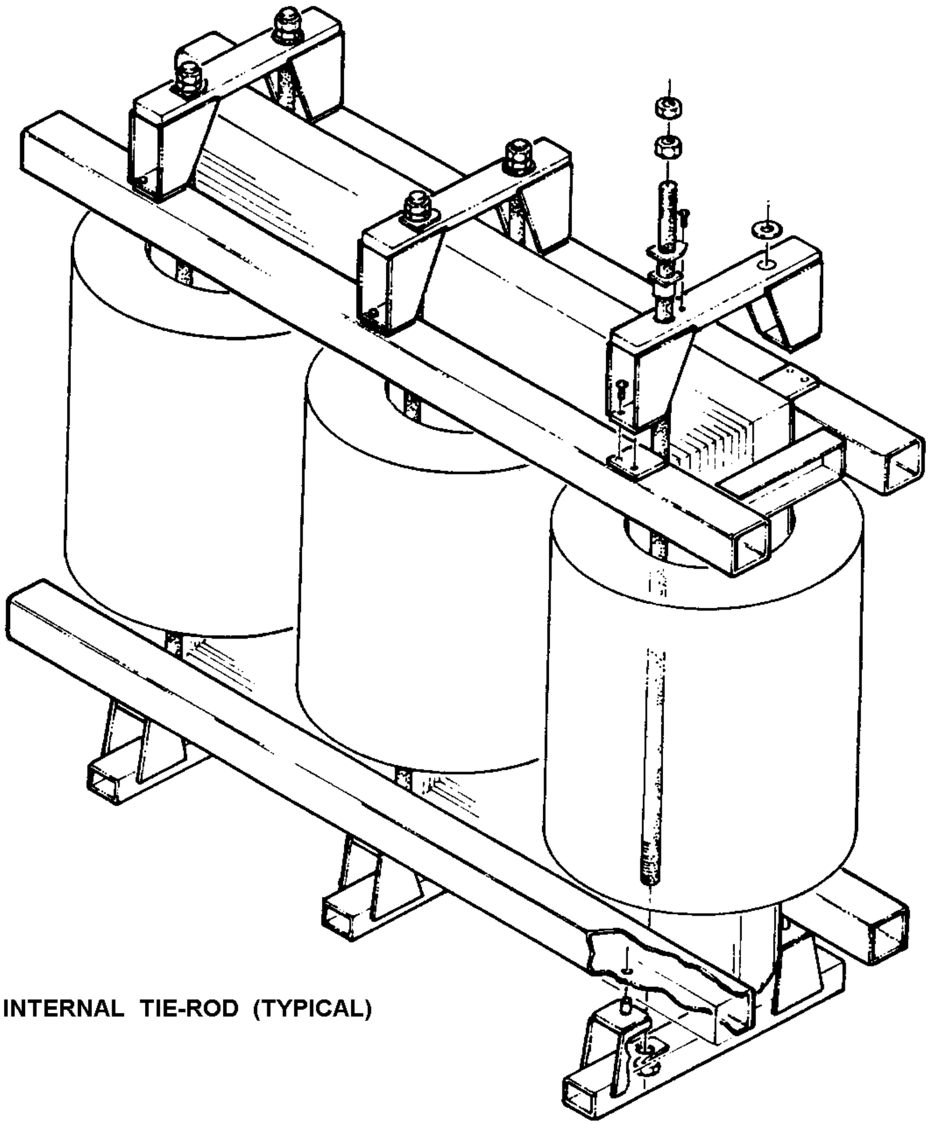
Buckling



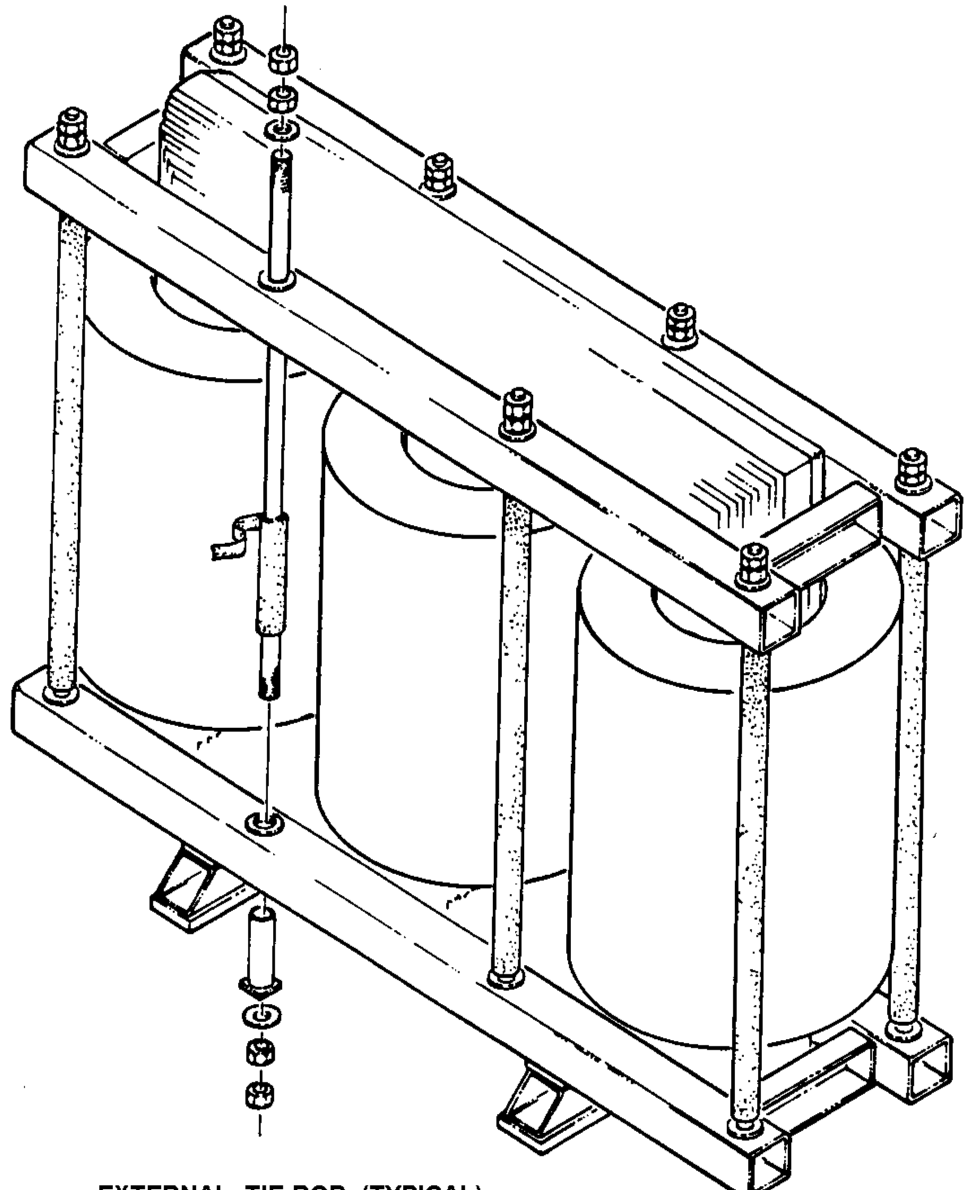
Hoop



Transformer Design:



INTERNAL TIE-ROD (TYPICAL)



EXTERNAL TIE-ROD (TYPICAL)

Loss Evaluation

Cost of ownership = capital cost + cost of losses

Cost of losses = cost of no-load loss + cost of load loss + cost of stray loss

The load loss and stray loss are added together as they are both current dependent

- Ownership of Transformer can be more than twice the capital cost considering cost of power losses over 20 years
- Modern designs = low-loss rather than low-cost designs

Loss Evaluation

Transformer as energy converter dissipates losses; depending on operation of the unit (load characteristics) the losses can have significant economical cost for users.

Losses are divided into:

- no-load loss
- load loss

Transformer also consumes some auxiliary power, resulting in auxiliary losses

Transformer Design:

Loss Evaluation
No-load loss

Losses generated in the core sheets by main (working) flux of a transformer are called no-load losses. They include the histeresis loss and the eddy current loss.

No-load losses **do not depend** on:

- load
- core temperature (there is though a correction factor)

No-load losses depend on:

- voltage, these losses increase dramatically with increase in voltage if flux density is approaching the saturation,
- frequency,
- core material: its properties, the lamination thickness, mass of the core.

Because most transformers are energized (under voltage) at all times, what results in continuous generation of no-load losses, these losses have high cost evaluation.

Loss Evaluation
load loss

Losses generated in transformer by load currents, both primary and secondary, are called load losses.

Load losses consist of

- fundamental (ohmic) losses I^2R in each phase, while resistance R is measured at DC voltage;
- additional (eddy) losses, generated by the eddy currents induced by the stray flux in all metallic elements (leads, windings, constructional parts, tank, shields) penetrated by this flux

Transformer Design:

Loss Evaluation

load loss

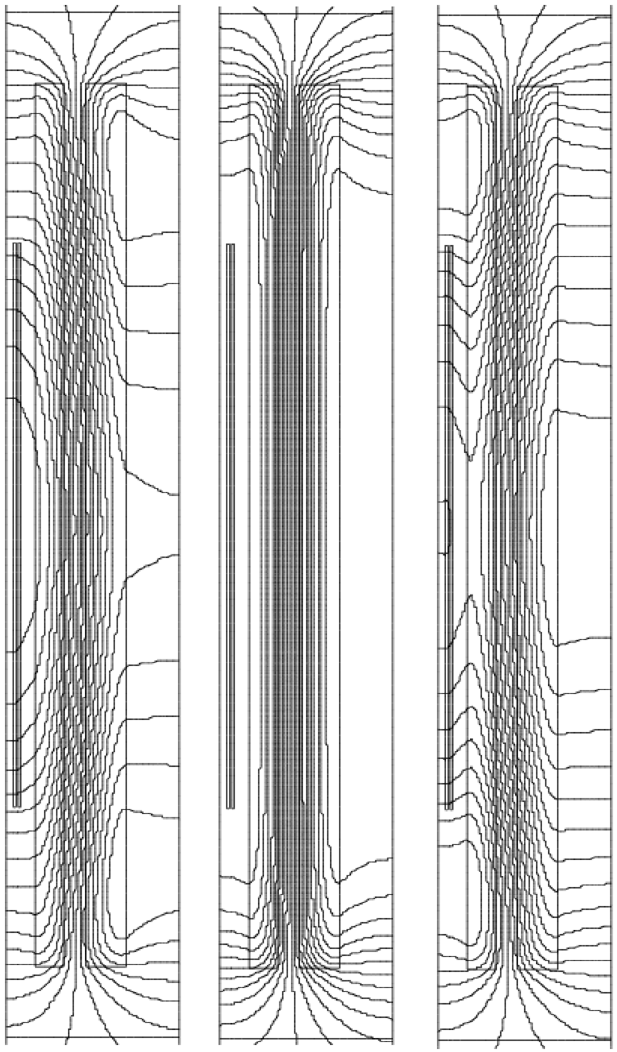
- Ohmic losses increase with resistance *R* which increases with the temperature *t* as follows:

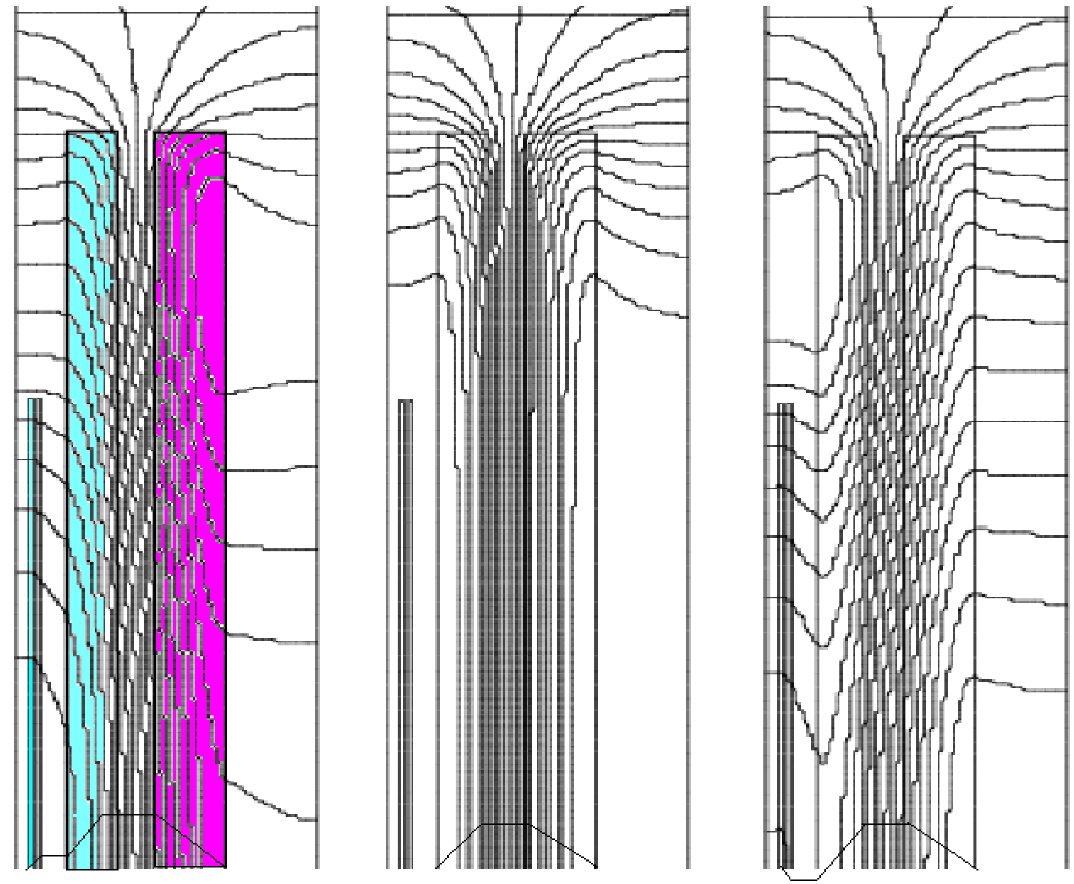
$$R_t = R_{t_{ref}} \frac{234.5 + t}{234.5 + t_{ref}}$$

- According to standards the additional losses decrease with increase in temperature (with reversed factor used for ohmic losses)
- Combined ohmic and eddy losses, giving total load loss, are increasing with square of load current; i.e. the load losses depend heavily on loading of the unit
- The standard reference temperature for the load losses of power and distribution transformers shall be 85^{o}C

Transformer Design:

Stray flux distribution



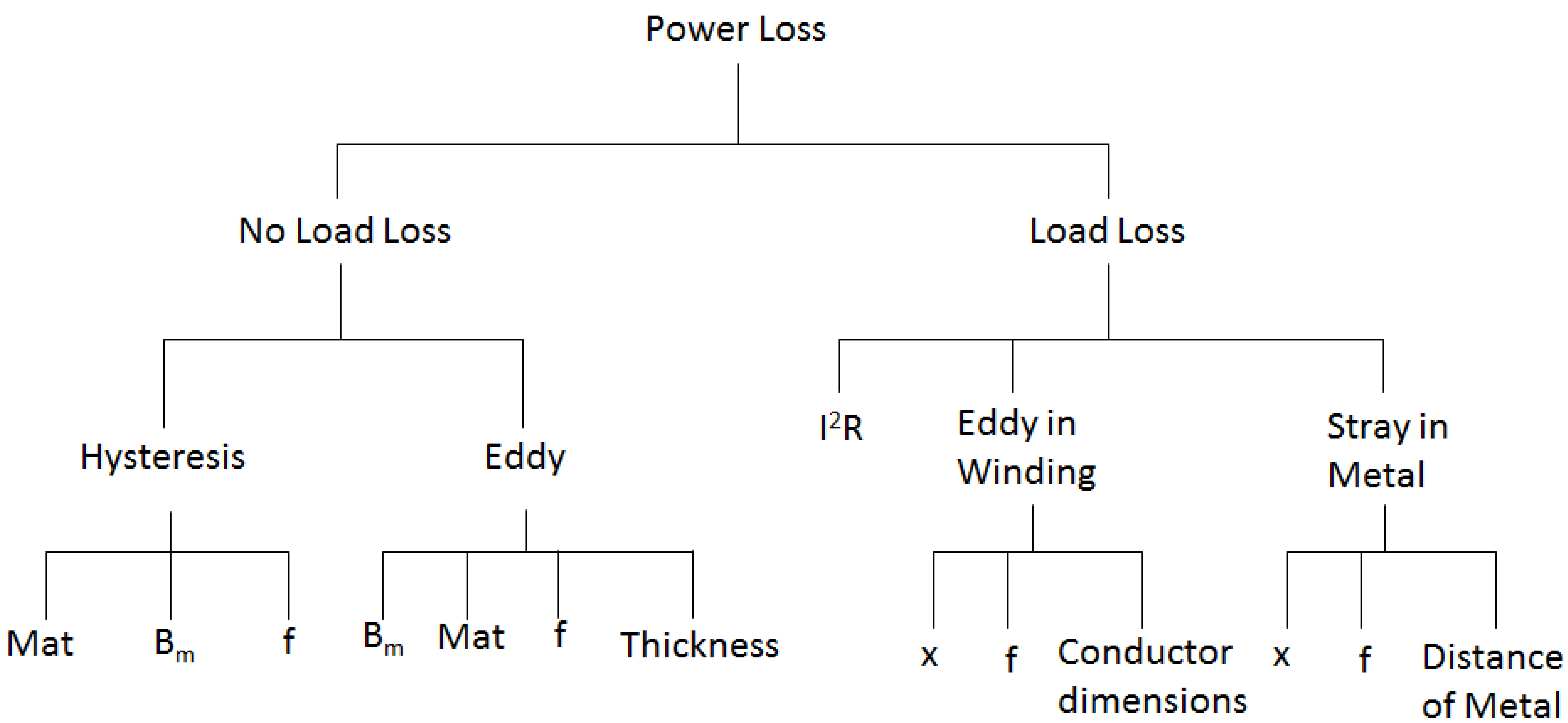


Flux distribution with the tapping winding in position:

(i) full rise, (ii) neutral, (iii) full buck

Transformer Design:

Summary of Losses



Loss Evaluation
Auxiliary losses

Auxiliary losses are generated by cooling equipment:

- fans,
- pumps.

Typically, these losses are not significant when compared to no-load and load losses.

The auxiliary losses depend on the cooling stage of the unit, reaching maximum for top power rating.

Loss Evaluation
Example

Typically, the losses are evaluated (in $) using customer-defined factors and are added to the price of transformer during bid evaluation

For example:

$Price\ adder = K_{NLL}\ x\ NLL + K_{LL}\ x\ LL + K_{AuxL}\ x\ AuxL$

where:

NLL, LL, AuxL- no-load, load and auxiliary losses [kW]

K_{NLL}, K_{NLL}, K_{NLL} - loss evaluation factors [$/kW]

Temperature rise limits

- Winding Temperature Rise:
  - average, 55/65°C, 95/115°C(nomex)
  - hot-spot, 65/80°C, 130/150°C (nomex)
  - hotspot, during short circuit 210°C
- Oil Temperature Rise:
  - top, 55/65°C
- Metal parts not in contact with insulation, 100°C
- Reference ambient temperatures
  40°C max, 30°C daily average, 20°C yearly average
  Any other ambient condition, the temperature rise limits to be reduced
- For water cooled units the ambient is considered that of cooling water

Transformer Design:

Temperature limits

- Oil temperature = 100/105^{o}C
- Average winding temperature(paper)= 85^{o}C for normal paper & 95^{o}C for thermally upgraded paper & 125 or 145^{o}C for nomex
- Hotspot winding temperature (paper) based on daily average ambient=95^{o}C for normal paper & 110^{o}C for thermally upgraded paper
- Maximum allowed hotspot based on maximum ambient =105^{o}C for normal paper & 120^{o}C for thermally upgraded paper
- Maximum allowed hotspot = 250^{o}C for very short time, during short circuit
- Temperature limit for metal parts in contact with insulation is same as for winding
- Other metal parts limit is 140^{o}C

Cooling

- Both no-load and load losses are converted into heat which increases the temperature of active parts (core and windings), constructional parts (clamps, tank), as well as of the oil.
- Next, the heat has to be dissipated by cooling system (tank, radiators, etc.) to cooling medium, e.g. to surrounding air. The temperature rises of all components are limited by appropriate standards. These criteria have to be satisfied during the temperature rise test (heat run).
- Intensity of cooling has to be increased together with increase in rated power, in order to sustain allowable temperature rises. In power transformers one may utilize: (i) radiators, or coolers, (ii) forced air flow, (iii) forced oil flow (preferably directed flow), (iv) water cooling, (v) “loose” structure of windings

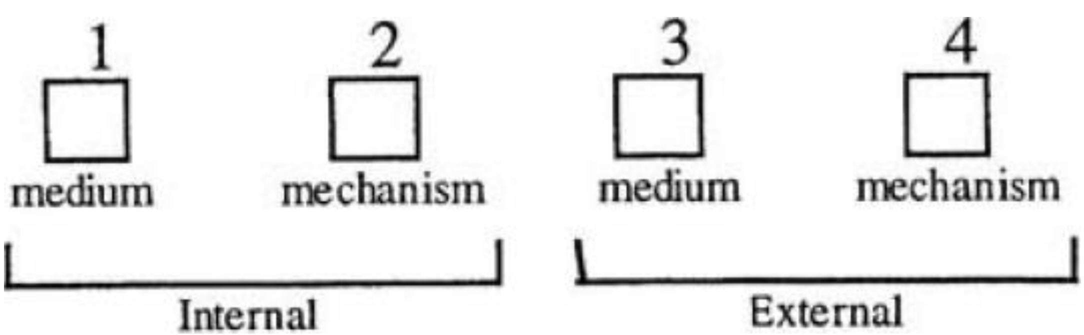
Cooling methods

Cooling medium

- A - air cooling,
- O - oil cooling,
- K, L - cooling with synthetic fluid,
- W - water cooling

Cooling mode

- N - natural cooling,
- F - forced cooling,
- D - directed cooling (directed oil flow)



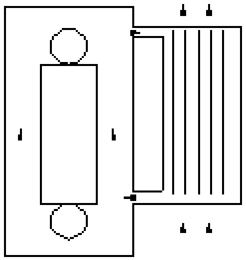
E.g. ONAN - oil natural, air natural, (OA)
ONAF - oil natural, air forced, (FA)
ODAF - oil directed, air forced (FOA)

Transformer Design:

Cooling

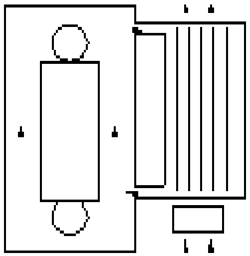
A) *ONAN, OA*

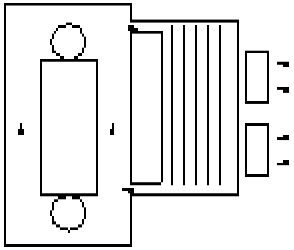
- Oil natural, air natural



B) *ONAF, FA*

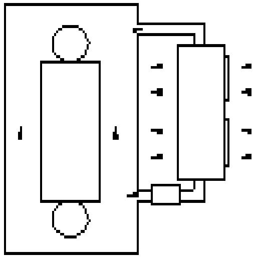
- Oil natural, air forced

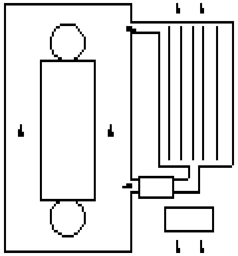




C) *OFAF, FOA*

- Oil forced, air forced





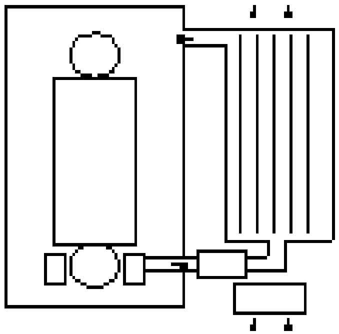
Transformer Design:

Cooling

D) *ODAF, FOA*

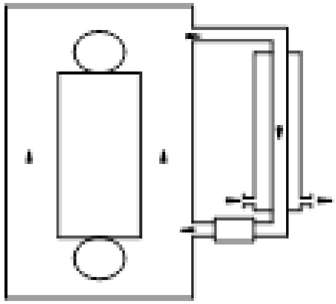
- Oil directed, air forced

- The oil is pumped and directed through some or all of windings



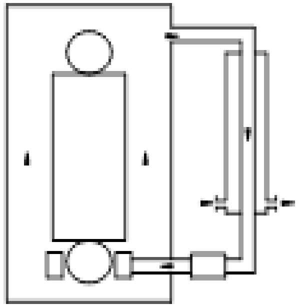
E) *OFWF, FOW*

- Oil forced, water forced



F) *ODWF, FOW*

- Oil directed, water forced



Overload & life expectancy

- Overload capability is limited by oil temperature & hotspot temperature
- Life is ended when probability of failure becomes too high
- Probability of failure is high when the tensile strength of paper is reduced by 80%
- Degree of polymerization is an indication of end of life.
- Loss of life when hotspot temperature exceeds 120^{o}C
- Rate of loss of life is doubled for every 8^{o}C over 120^{o}C
- There is gain of life when temperature is less than 120^{o}C
- Check for 24hour period if there is any additional loss of life for any specified load cycle
- ANSI gives method for calculation

Sound Level (ANSI)

- Produced by magnetostriction in core caused by varying magnetic flux; fundamental frequency is double power frequency (100 or 120 Hz)
- Sound level of energized unit depends on:
  - core material
  - magnetic flux density in core
  - core weight (because core weight is higher for higher power rating, sound level increases proportionally to log(MVA)
  - tank design and cooling system (# and type of fans, pumps)
- Measured at *0.3 m* for core alone and at *2 m* for top rating (with whole cooling equipment on)
- ANSI does not cover Sound Level under load

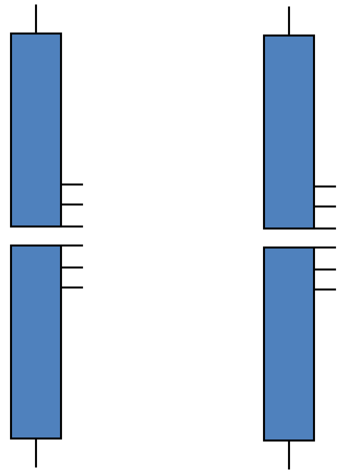
Tap changers

- De-energized type changers (bridging, linear, series/parallel, delta/star) - the reconnection is realized for de-energized unit
- Load tap changers (LTC) - designed to change the voltage under load

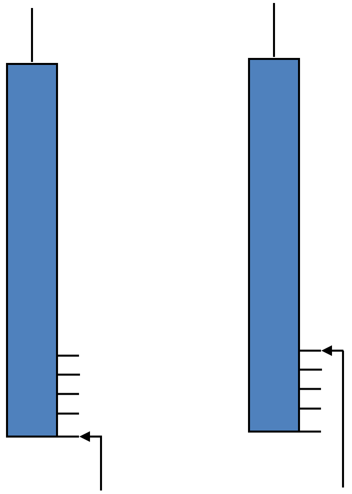
Tap changers - DTC

Typically used to vary HV by ±5% in 4 steps (2.5% voltage change per step), or ±10% in 4 steps

bridging type



linear type



Tap changers - LTC

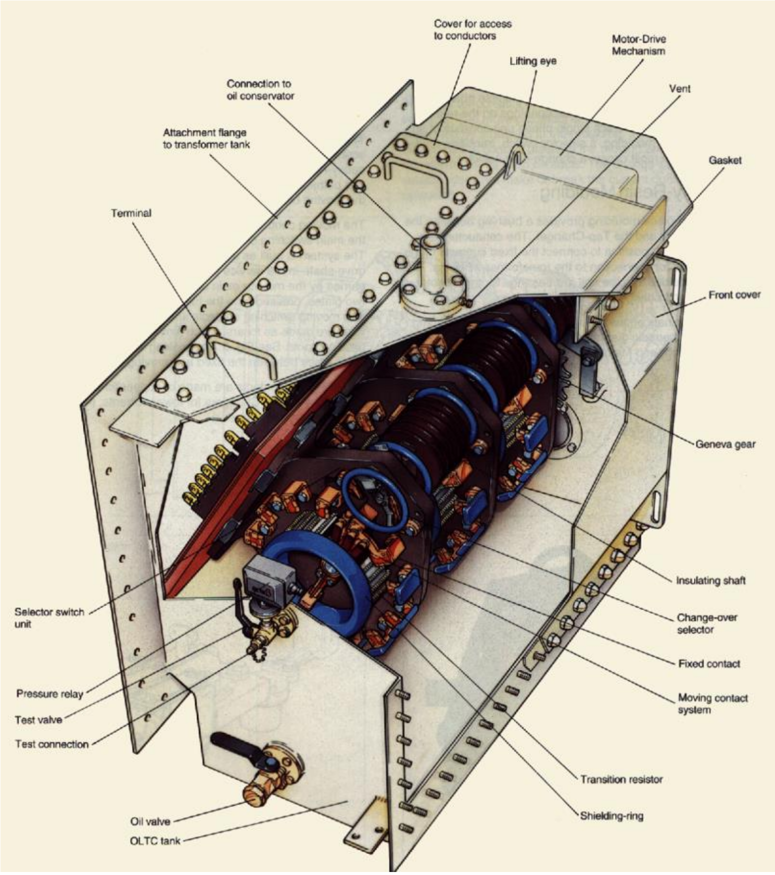
- On-load tap changers are mainly used for power transformers and autotransformers; the change of tap position is realized without de-energizing the unit, under load
- LTC are built as:
  - resistive type (B.Jansen),with current-limiting resistors
  - reactive type, with preventative autotransformer (reactors)

Tap changers - LTC with resistors

- Resistive type LTC performs switching with main switching contact and two transition contacts with resistors; typically equipped also with reversing switch
- During normal operation (at given tap position) the current is carried by the main switching contact only
- during changing the tap position, the transition contact are switched on and carry current through resistors
- Move of main contact creates arcing (a few ms duration), total cycle (switching sequence) takes ~50ms

Tap changers - LTC with resistors

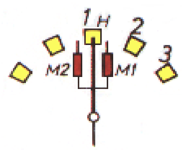
- Resistance used to prevent excessive current flow between taps
- The switching mechanism operates extremely quickly to limit heating in the resistor during the bridging step of a tap change
- Continuous operation in a bridging position is not possible



Transformer Design:

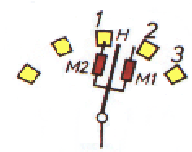
L.T.C. with resistors- ABB UZE/F

Fig. a



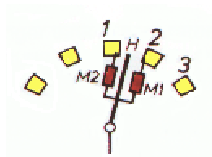
Position 1. The main contact H is carrying the load current. The transition contacts M1 and M2 are open, resting in the spaces between the fixed contacts.

Fig. b



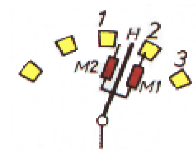
The transition contact M2 has made on the fixed contact 1, and the main switching contact H has broken. The transition resistor and the transition contact M2 carry the load current.

Fig. c



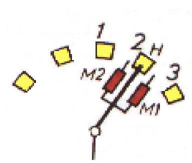
The transition contact M1 has made on the fixed contact 2. The load current is divided between the transition contacts M1 and M2. The circulating current is limited by the resistors.

Fig. d



The transition contact M2 has broken at the fixed contact 1. The transition resistor and the transition contact M1 carry the load current.

Fig. e



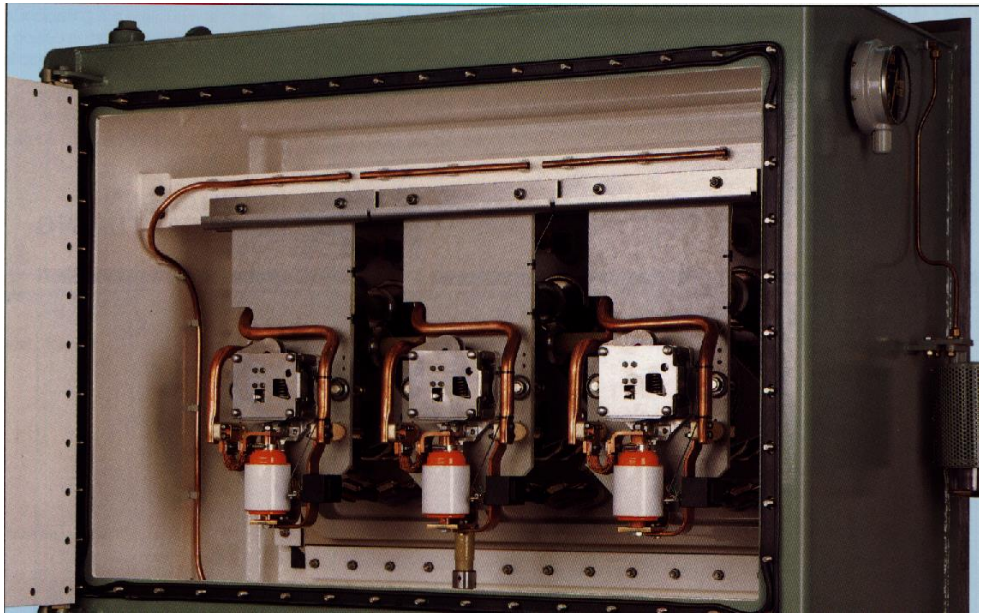
Position 2. The main switching contact H has made on the fixed contact 2. The transition contact M1 has opened at the fixed contact 2. The main contact H is carrying the load current.

Tap changers - LTC with reactors

- Reactive LTC uses reactors to limit current during switching; because reactor can be designed as permanently loaded with trough-current of LTC, one may use bridging position to double the number of steps in LTC
- Typically, reactive-type LTC uses two reactors (two parallel branches), two by-pass switches, selector switch with two contacts and vacuum interrupter; also reversing switch is used to double the number of steps
- the entire tap changer mechanism is enclosed in the oil-tight compartment, separated from main transformer tank

Tap changers - LTC with reactors

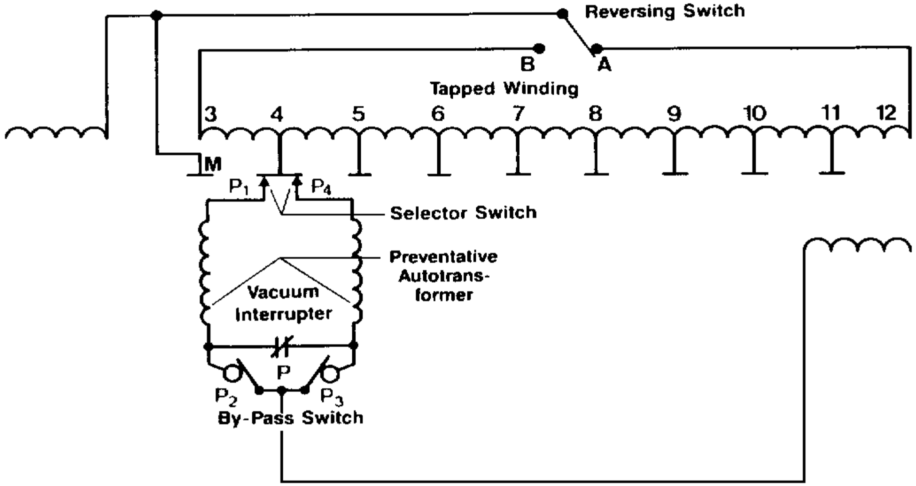
- Typically a center-tapped reactor (or preventive auto-transformer) is used to prevent excessive current flow between taps
- Continuous operation in a bridging position is possible, which results in fewer leads



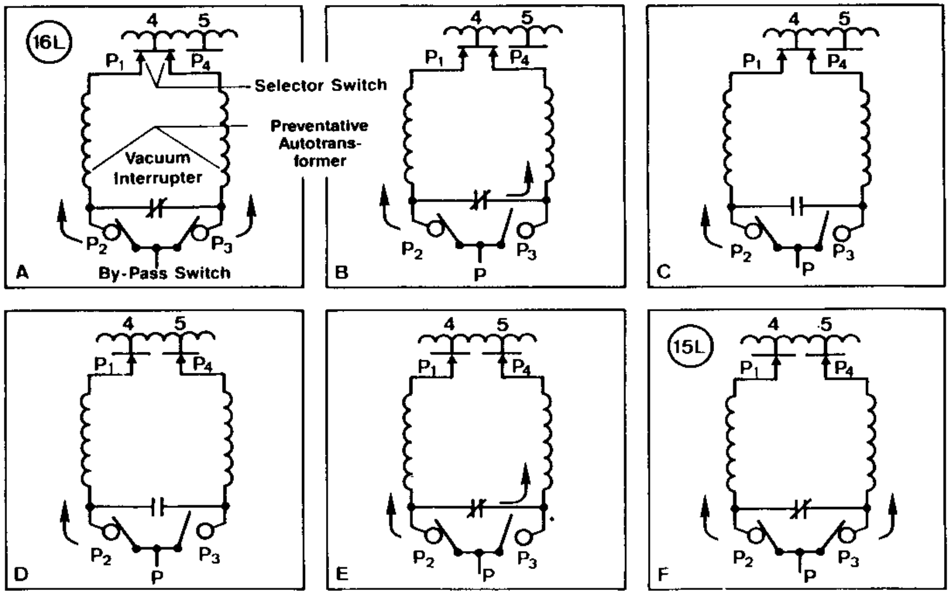
Transformer Design:

LTC with reactors - MR RMVII

Typical RMV -II winding layout (L.T.C. on position 16 L)

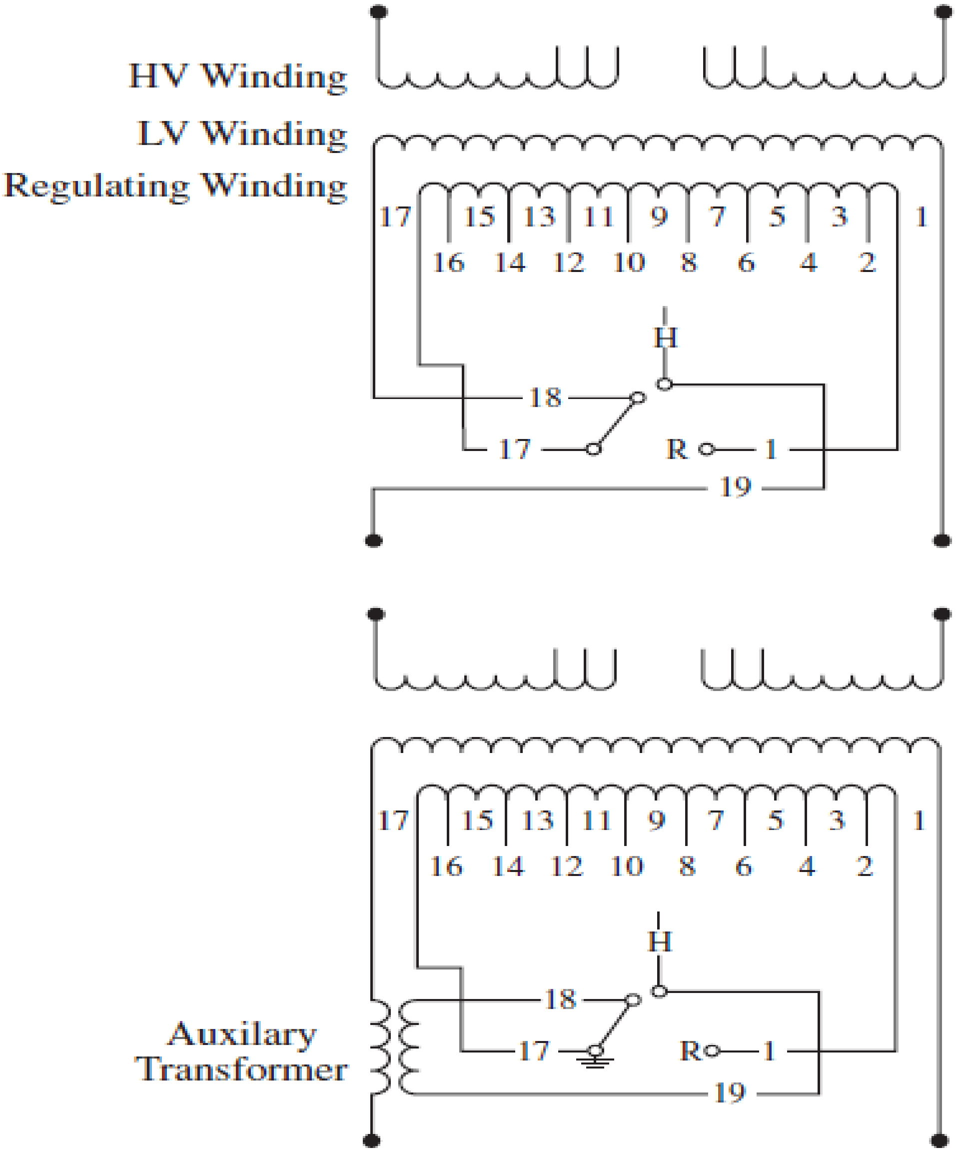


Tap change sequence from position 16 L to 15 L



Transformer Design:

Tap Changer: Schematic and Connection Chart



Volts L-L	LTC Positions	R Connects at Direction		H Connects
		Raise	Lower	
14520	16R	18 – 1	18 – 1	17 – 19
14438	15R	18 – 1	18 – 1	16 – 19
14355	14R	18 – 1	18 – 1	15 – 19
14272	13R	18 – 1	18 – 1	14 – 19
14190	12R	18 – 1	18 – 1	13 – 19
14108	11R	18 – 1	18 – 1	12 – 19
14025	10R	18 – 1	18 – 1	11 – 19
13943	9R	18 – 1	18 – 1	10 – 19
13860	8R	18 – 1	18 – 1	9 – 19
13778	7R	18 – 1	18 – 1	8 – 19
13695	6R	18 – 1	18 – 1	7 – 19
13613	5R	18 – 1	18 – 1	6 – 19
13530	4R	18 – 1	18 – 1	5 – 19
13447	3R	18 – 1	18 – 1	4 – 19
13365	2R	18 – 1	18 – 1	3 – 19
13283	1R	18 – 1	18 – 1	2 – 19
13200	RN	18 – 1	18 – 1	1 – 19
13200	N	18 – 17	18 – 17	18 – 19
13200	LN	18 – 17	18 – 17	17 – 19
13118	1L	18 – 17	18 – 17	16 – 19
13035	2L	18 – 17	18 – 17	15 – 19
12953	3L	18 – 17	18 – 17	14 – 19
12870	4L	18 – 17	18 – 17	13 – 19
12788	5L	18 – 17	18 – 17	12 – 19
12705	6L	18 – 17	18 – 17	11 – 19
12623	7L	18 – 17	18 – 17	10 – 19
12540	8L	18 – 17	18 – 17	9 – 19
12458	9L	18 – 17	18 – 17	8 – 19
12375	10L	18 – 17	18 – 17	7 – 19
12293	11L	18 – 17	18 – 17	6 – 19
12210	12L	18 – 17	18 – 17	5 – 19
12128	13L	18 – 17	18 – 17	4 – 19
12045	14L	18 – 17	18 – 17	3 – 19
11963	15L	18 – 17	18 – 17	2 – 19
11880	16L	18 – 17	18 – 17	1 – 19

Transformer Design:

RCBN or FCBN?

- RCBN – reduced capacity below nominal
  - MVA is reduced in lower voltage tap positions; current can not be greater then nominal voltage position
  - used mainly for LTC taps in LV
    i.e. +/- 10% LTC
- FCBN – full capacity below nominal
  - MVA is constant in lower voltage tap positions; current can be greater then the nominal voltage position
  - always the case for DTC taps and HV LTC
    i.e. +/- 5% DTC

Q&A?