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Biography

Mr. Sanjay Y. Patel is the Manager, Electrical Design-North America for Smit Transformers. He received is B.S in Electrical Engineering (Major "Electrical Machine Design") from M.S. University Of Baroda, India in 1985. His graduate work thesis was on "Manufacturing Process of Power Transformers". He joined Smit Transformers in 1993, and has been mainly responsible for electrical design of transformers from 10 MVA up to 1000 MVA, BIL 1675 kV. Prior to joining Smit, he worked as a Design Engineer for Nik-San Engineering in India and as a Design Engineer for L. Wilson Power Corporation, Minneapolis, MN and Magnetek Ohio Transformers, Rancho Dominguez, CA. Mr. Patel has authored several papers on the subject of transformer design. He is a member of IEEE Transformer Committee.

SPECIAL DESIGNS AUTO-TRANSFORMERS

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INTRODUCTION

Electric Power Generation in the US has seen a constant increase in installed capacity during the past century. The load centers being remote from the generating stations, combined with the increase in power generation naturally resulted in extensive transmission networks thus the need for transformers of large capacity. For better reliability and economic viability, the various isolated high voltage power networks are inter-connected by means of **Auto-Transformers**.

Though the advantages of Auto-Transformers have been known for a long time, they were not used as power units but only as auxiliary devices for fine voltage adjustments, for starting induction motors and so on. The recent de-regulation of the utility industry, however, has caused major changes. Utilities have merged to consolidate their resources, which resulted in superimposing power grid(s) on power grid(s), further increasing the demand for larger capacity network/grid inter-connecting Auto-Transformers.

The fact that Auto-Transformers have weight and overall dimension that is less than 2-winding transformers of the same outputs permits them to be produced with a considerably larger capacity per unit. Auto-Transformers, however, call for several unique design considerations which require special attention and careful study. Auto-Transformers discussed here are those of **core form** design and **Y-**connected for high-voltage networks and serving mainly as inter-connecting transformers.

ADVANTAGES OF AUTO-TRANSFORMERS AND WHY

Auto-Transformers have several advantages over 2-winding transformers of the same outputs, such as lower weight (hence lower cost), lower losses (hence higher efficiency), better regulation as lower impedance, smaller exciting current as lower core weight and smaller overall size, which is especially important for the large power units or for units where shipping size and weight is of importance.

The key to these advantages, in comparison to a 2-winding transformer of the same output, is the kVA that it transforms (and the size of a unit is proportional to the kVA that it transforms), which is explained as follows.

The primary and secondary windings of 2-winding transformers are <u>not</u> connected electrically, and there is only magnetic linkage between them. All the power is transformed from the primary to secondary winding electromagnetically (transformer action also referred to as "Total or Name Plate or Transformed or all - kVA), FIGURE 1-a. On the contrary, the windings of Auto-Transformers are connected electrically so as to form a single continuous winding, a portion of which is common to both the primary and secondary circuits. Owing to this fact, some portion of the power (referred to as "Electrical or Conductive - kVA") passes directly from the primary to secondary side without transformation and the remaining portion of the power is transformed from the primary to secondary side electromagnetically (FIGURE 1-b).

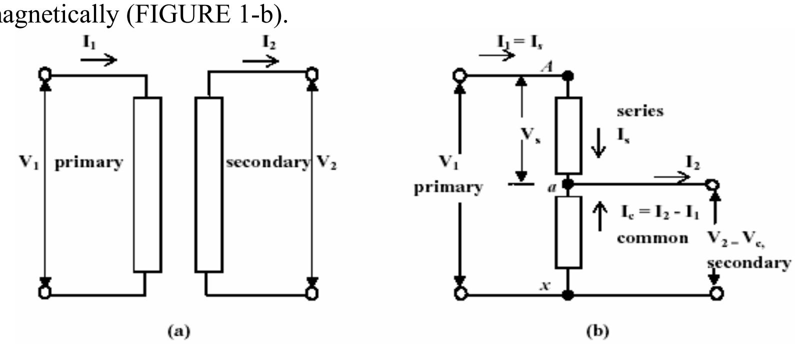


FIGURE 1. single-pahse schematic of:
(a) 2-winding transformers, (b) step-down auto-transformer

The Auto-Transformer does not differ from that of the ordinary transformer under conditions of no-load. The applied voltage V_1 is uniformly distributed among the turns of winding *Ax* carrying the no-load current, hence the voltage per turn is the same throughout the winding and the secondary voltage V_2 is proportional to the number of turns in the common winding *ax*:

$$V_2 = V_{ax}$$

The transformation ratio “k” of the Auto-Transformer is:

$$k = V_1 / V_2 = V_{Ax} / V_{ax}$$

Consider the operation of a loaded Auto-Transformer (assuming the no-load current is negligible). It is clear from the above figure that current I_1 ($=I_s$) flows in the primary side, while the secondary side (load circuit) carries current I_2, current I_c flowing through the common winding *ax* is equal to the difference of I_2 and I_1:

$$I_c = I_2 - I_1$$

Thus, the secondary current I_2 consists of two components – the primary current I_1 which flows through the series winding *Aa*, by-passing the common winding *ax*, and current I_c flowing through the common winding ax and equal to $I_2 - I_1$. Correspondingly, the secondary power P_2 also consists of two components – the Electrical kVA (“P_e”) which is directly transferred from the primary to the secondary circuit through the series winding *Aa,* and the electromagnetic kVA (P_{eq}) which is transferred to the secondary circuit by transformer action. The total kVA = $V_1 * I_1 \approx V_2 * I_2$

It is clear from the above that the secondary (common) winding of the Auto-Transformer is calculated for the difference of currents ($I_2 - I_1$), rather than for the secondary current I_2 (as would be the case in a 2-winding transformer), while the primary (series) winding is calculated for the difference of voltages (V_1-V_2) rather than the primary voltage V_1 (as would be the case in a 2-winding transformer). It is this fact that explains the economic advantage of Auto-Transformers. (NOTE: We can refer to the series and common winding as primary and secondary windings as the kVA of each branch are equal and their m.m.f's (ampere-turn “AT”) are in opposition).

The above theory can be 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” = $P_{NP} - P_{eq} = P_{NP} * (1- \alpha)$

From the above equation (for co-ratio) it follows that the equivalent kVA is by a factor of α less than the name plate kVA, the values of α being most advantageous with the ratio of transformation approaching unity. The co-ratio is of primary importance, defining the most of the Auto-Transformer parameters. As geometrical dimensions of an Auto-Transformer are defined by the electromagnetic power (P_{eq}), the size of the Auto-Transformer will be less for less co-ratio, that is when the voltage ratio “k” is closer to unity.

The example below illustrates the advantages of the Auto-Transformer over a 2-winding transformer.

Example. A power of 100 mVA (single-phase) is to be transferred from a line (connected Grd. Wye) with a voltage of 230 kV to another line (connected Grd. Wye) with a voltage of 115 kV.

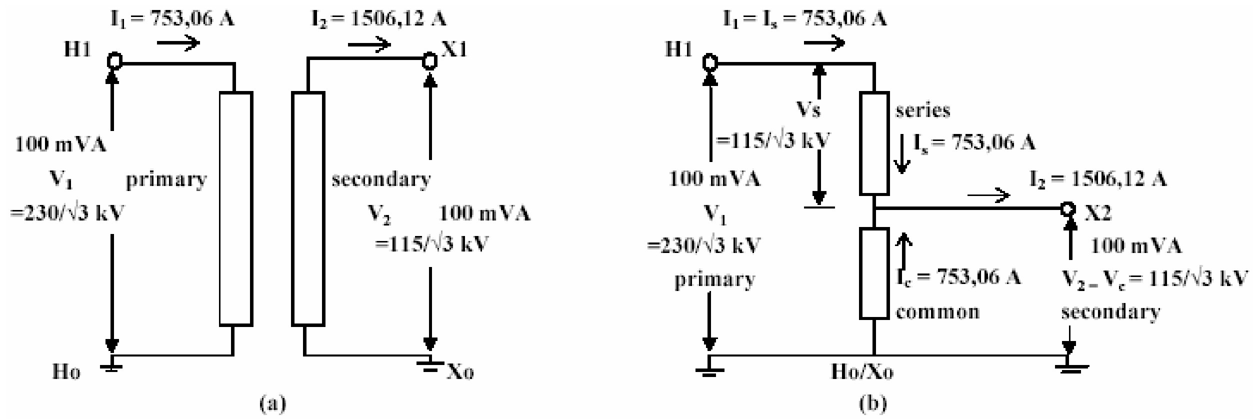


FIGURE 2. single-pahse 100 mVA, 230/115 kV
(a) 2-winding transformers, (b) step-down auto-transformer

kVA calculation for;

<u>For 2-winding transformer</u>

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

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

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

<u>For Auto-Transformer</u>

Transformation ratio = 230 / 115 = 2

The co-ratio α = 1 – 1 / 2 = 0.5

Equivalent kVA "P_{eq}" = 100,000 * 0.5
= 50,000 kVA

OR can be calculated as

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

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

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

Electrical kVA "Pe" = 100,000 * (1-0.5)
= 50,000 kVA

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

As seen from the above, for the 2-winding transformer, all the power is transferred from primary to secondary by transformer action and hence is calculated for 100 mVA. In the case of the Auto-Transformer, only half (defined by the value of α) of the power is transferred to the 115 kV line by transformer action (P_{eq}) and the other half of the power (Pe) is transferred form the primary to secondary directly, hence the Auto-Transformer can be calculated for 50 mVA only. It is due to this very fact that the Auto-Transformer has lower cost (as lower weight of active parts), lower exciting current, lower total losses (hence higher efficiency) and smaller overall size.

DISADVANTAGES OF AUTOTRANSFOMERS AND WHY

Well as they say "Nothing comes for free". Auto-Transformers do have disadvantages, which should be weighed against the above mentioned advantages before determining a preference on the type of transformer design is made.

Effective percentage impedance ($\%Z_{sc\text{-}auto}$) of an Auto-Transformer is equal to that of the 2-winding transformer ($\%Z_{sc}$) of the same rating multiplied by the co-ratio α:

$$\%Z_{sc\text{-}auto} = \alpha * \%Z_{sc}$$

Example: Consider a 100 mVA, 115 – 115 kV 2-winding transformer with percentage impedance ($\%Z_{sc}$) of 10 % @ 100 mMVA base FIGURE 3-a. If the same transformer is connected as an Auto-Transformer (the equivalent Auto-Transformer rating will be 200 MVA, 230-115 kV) then the percentage reactance as an Auto-Transformer FIGURE 3-b.

$$\%Z_{sc\text{-}auto} = \alpha * 10 = \mathbf{5\ \%}\ @\ 200\ \text{mVA} \qquad (\text{as } \alpha = 0.5)$$

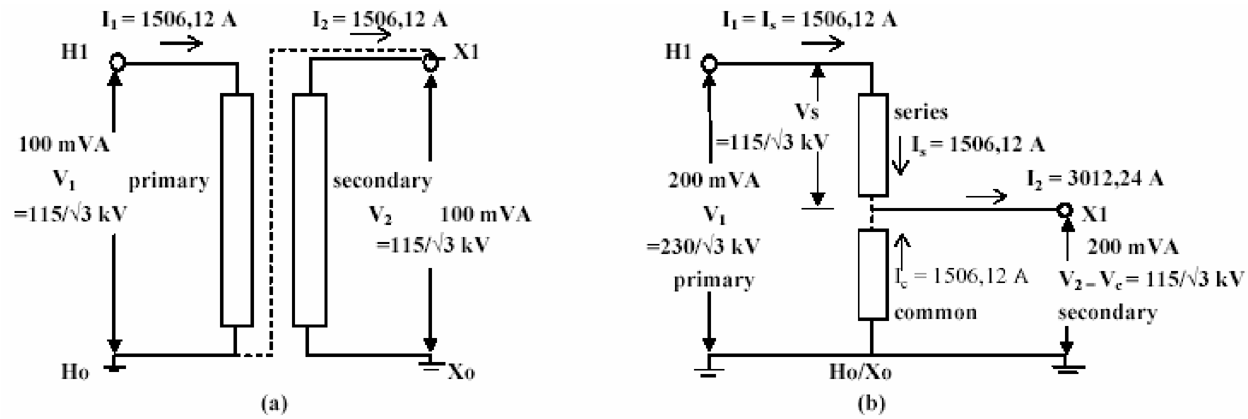


FIGURE 3. single-pahse 100 mVA,
(a) 2-winding transformers, 115-115 kV (b) step-down auto-transformer, 230-115 kV

For the above example, the short-circuit currents of the unit in Auto-Transformer connection will be 2 times as large (as short-circuit currents are inverse proportional to the impedance) and the short-circuit stresses 4 times as large (as short-circuit stresses are inverse square proportional to the current) as in 2-winding connection. Owing to this fact, special attention must be given to study the short-circuit stresses and adequate design techniques **(careful winding designs based on magnetic leakage field plots such as FEA programs is required to effect minimum m.m.f. (ampere turn unbalance between windings)** should be employed to withstand these stresses.

Auto-Transformers equipped with no-load tap changers (NLTC) and/or load tap changers (LTC) for voltage regulation (of HV and/or LV voltage) represent a greater problem than as compared to 2-winding transformer. One such case is when the HV (series) windings of the Auto-Transformer are designed with taps on the main body of the series winding FIGURE 4.

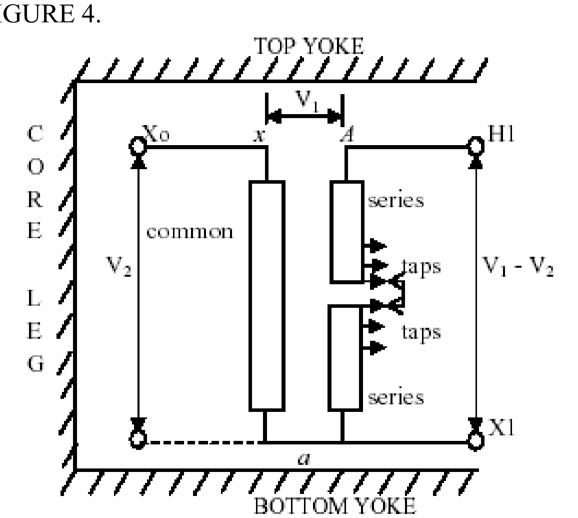
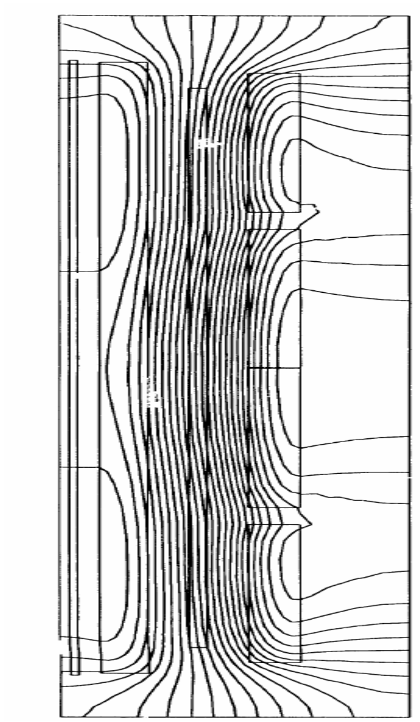


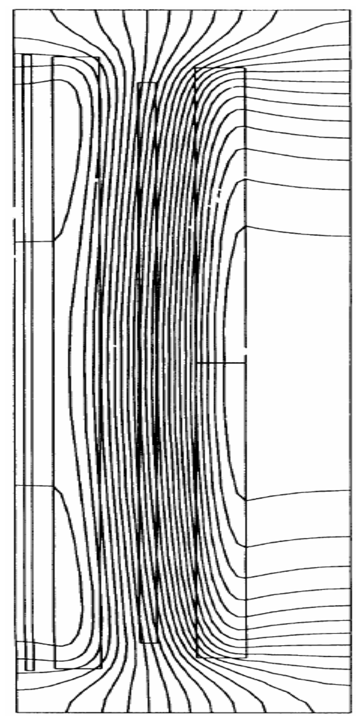
FIGURE 4. Arrangment of tappings in main body
of series winding of an auto-transformer

For the above scheme, if voltage regulation (either for NLTC or LTC application) of ± 5% of HV is required, then the taps will occupy about 10%/**α** portion of the series winding (it will be 10% in case of 2-winding transformer), as the series winding is only **α**th portion of the total winding connected to the HV (V_1) voltage. For example, if **α** = 0.5 and voltage regulation required is ± 5%, the taps will occupy 20% of the series winding (it will be 10% in case of 2-winding transformer). Therefore, larger inequality in m.m.f. (Ampere Turn) distribution will take place in Auto-Transformer than in 2-winding transformer, resulting in higher mechanical axial forces. If the axial forces are not manageable then the tapings should be provided on a separate tap winding, the physical location of which is on the core leg in respect to other windings. This is of great importance as the location of the tap winding influences the impedance profile of the Auto-Transformer (this is discussed in detail in later section). Once again, this requires an intensive study of short-circuit duty of an Auto-Transformer utilizing FEA programs for magnetic field plots FIGURE 5-a, b, c &d.



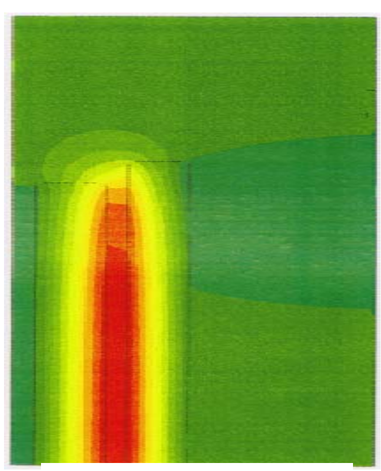
(a) auto-transformer with taps in the main body of series wdg

(a)

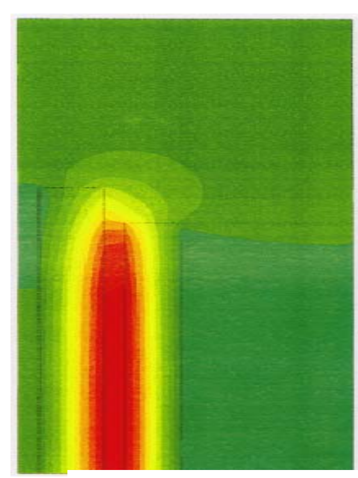


(b) auto-transformer with taps in a separate tap wdg. Influence of winding height on leakage flux

(b)



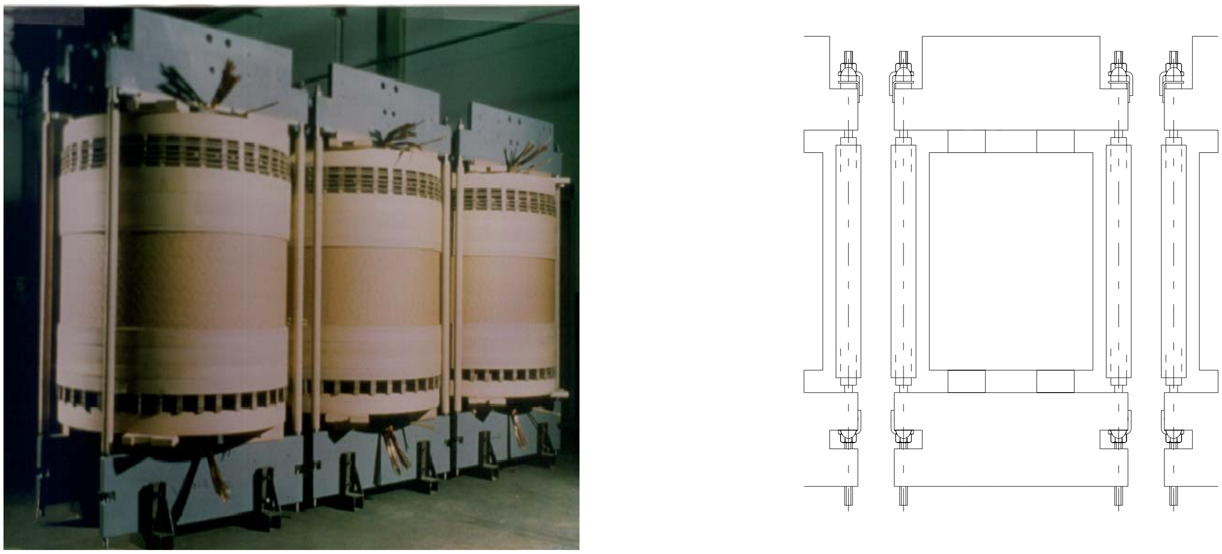
(c) LV shorter than HV



(d) LV taller than HV

FIGURE 5. Leakage Magnetic Field Plot using FEA program(s)

Due to these high mechanical axial forces, special care must be taken to ensure that the transformer is able to withstand the mechanical stresses without any failure of the windings or the active parts. Examples of some techniques used by SMIT are: 1) Restrict/minimize axial insulation in the windings as much as possible thus improving the dynamic behavior of the windings; 2) Use of epoxy bonded CTC (Continuously Transposed Cable) as winding conductor; 3) Provide maximum radial support on winding turns for which SMIT employs a very unique "independent" core & coil clamping structure FIGURE 6-a & b.



(a) SMIT windings with individual phase clamping (b) Uniform radial support

FIGURE 6. SMIT Core & Coil Clamping Structure

Electrical connection of the Auto-Transformer windings can result in that the equipment in the low voltage side may happen to be under high potential. One possible case of such a condition is when there is single line to ground fault on the HV system with isolated neutral, another line on the HV and LV (and hence common winding) side and also the equipment connected on the LV side (generator etc.) will get HV potential relative to ground FIGURE 7. To avoid this disadvantage the Auto-Transformer should operate in networks with a neutral solidly grounded or grounded through small impedance. This leads to increase in single-phase short-circuit currents which may be more than the three-phase values (thus the study of short-circuit duty of an Auto-Transformer is more intensive).

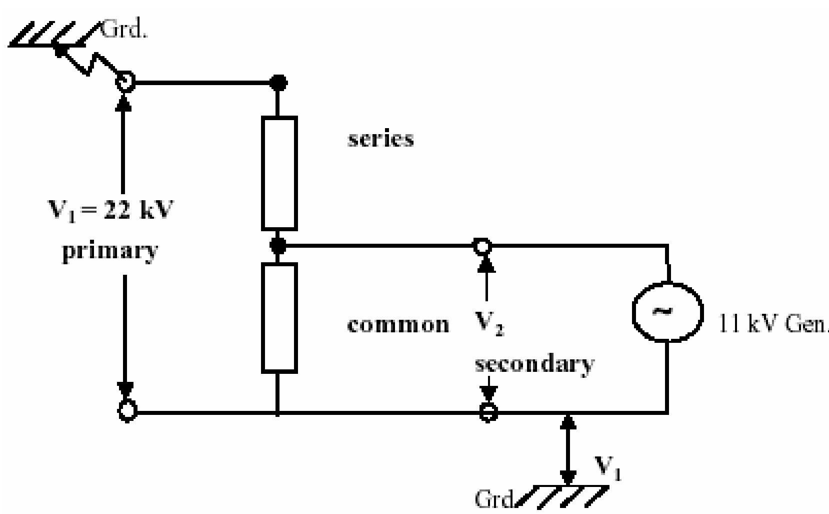


FIGURE 7. Appearance of high voltage in the LV side due to Auto-Transformer connection

Over-voltages in Auto-Transformers can have a more severe character than in 2-winding transformers because of the existence of *electrical connection* between the primary and the secondary sides. FIGURE 8 shows an Auto-Transformer with grounded neutral. The surge wave can reach the Auto-Transformer from either the LV or HV side. In the case when a surge comes from the LV side, the voltage distribution along common (*ax*) winding will be similar to that in a transformer winding with grounded neutral (FIGURE 9-a). The voltage distribution along series (*aA*) winding depends upon whether the winding is switched on to the line or not. In the first case, the series winding is grounded through the surge impedance of HV line and the voltage distribution will have the same character as in common winding. In the second case, the series winding has the effect of an isolated neutral and the initial voltage distribution will correspond to FIGURE 9-b. (Refer to FIGURE xx for an actual calculation for this case).

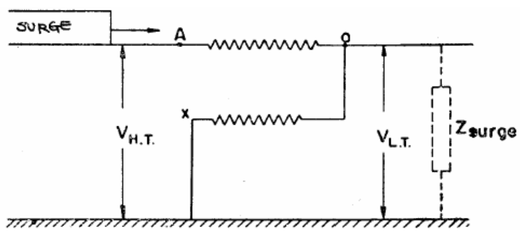
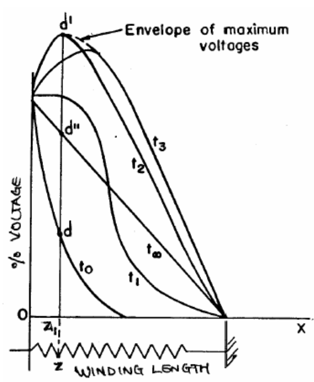
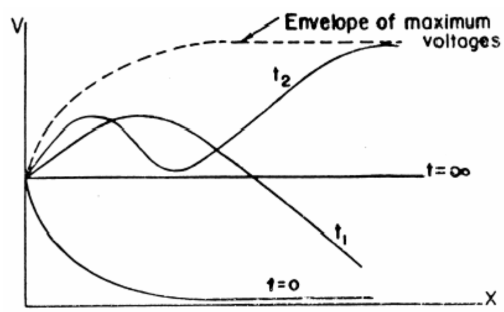


FIGURE 8.Auto-Transformer with grounded neutral (surge from the HV side).



(a) Grounded neutral



(b) Isolated neutral

FIGURE 9. Voltage distribution along a transformer winding with: (a) Grounded neutral, (b) Isolated neutral

When a surge comes from the HV side, terminal *a* may be considered to be grounded through surge impedance of the LV line and the voltage distribution along series winding will be similar to that of a transformer with grounded neutral FIGURE 9-a. At the same time, a surge voltage will be induced in winding ax, the maximum value taking place in the middle of the winding as both ends are in effect grounded. If the number of turns of common winding is considerable more (for example for $\alpha = 0.33$) than that of the series winding, the induced surge voltage in the common winding may exceed admissible values FIGURE 9-c.

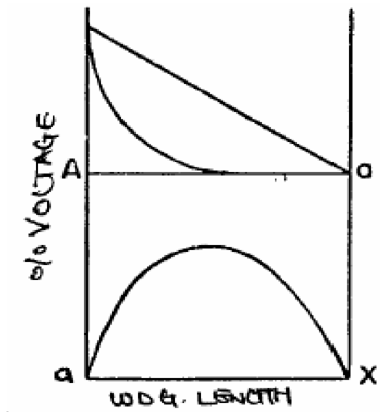
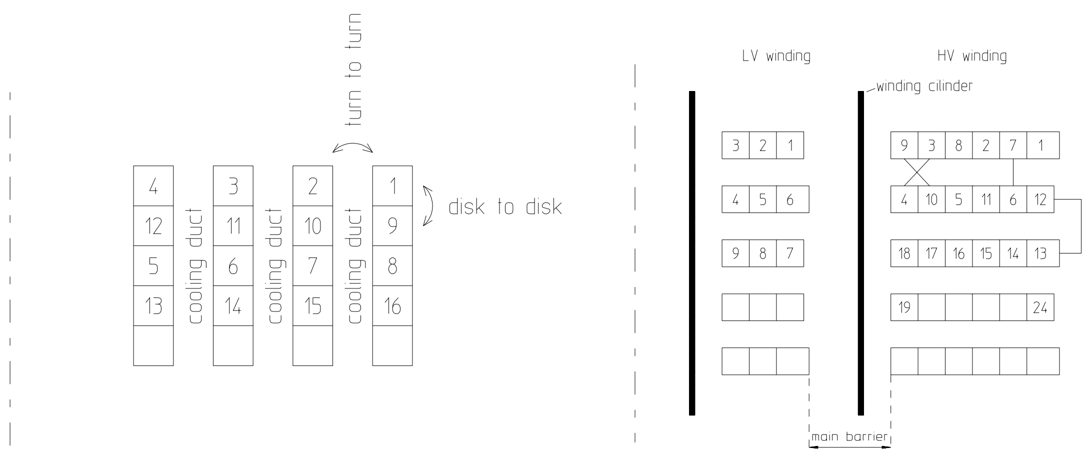


FIGURE 9. (c) Voltage distribution in the windings of an Auto-Transformer, surge from HV side.

In view of the above, the Auto-Transformer should be adequately protected internally (bushing inwards-the transformer) as well as externally (bushing outwards-proper use of Lightning arrester, etc).

The *internal* protection is achieved by proper selection of winding design (such as interleaved disk windings, etc.), FIGURE 10 –a & b, and intensive study of the behavior of the active parts to voltage surges, employing the use of FEA program for electrostatic field plots FIGURE 11 and impulse programs capable of handling the inductance-capacitance (LC) circuit of the active parts (core and coils) FIGURE 12. Once the study is completed, a clear and concise layout drawing of the active parts should be done highlighting the maximum voltage stresses FIGURE 13.



(a) SMIT design (b) Other conventional designs

FIGURE 10. Interleaved HV disk windings

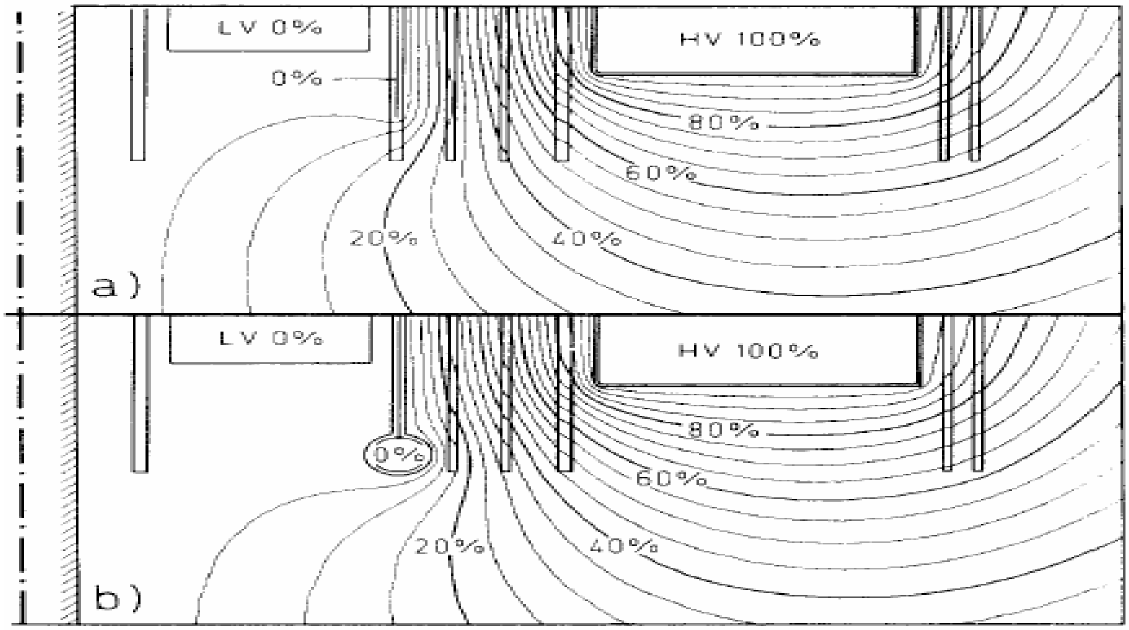
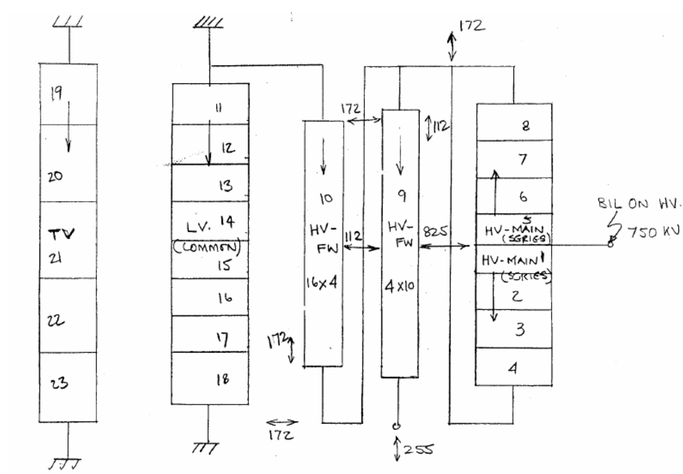
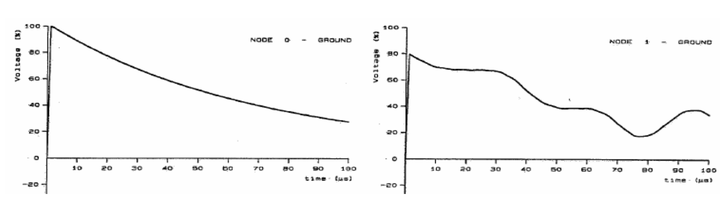


FIGURE 11. Electrostatic filed plot of the end space of a transformer
(a) Shielding cylinder with sharp-ended strips, (b) Shielding ring for relieving the strip ends

The study of the transformer winding behavior under impulse stress is done by modeling the entire core and coils as a lumped LC circuit as shown below:



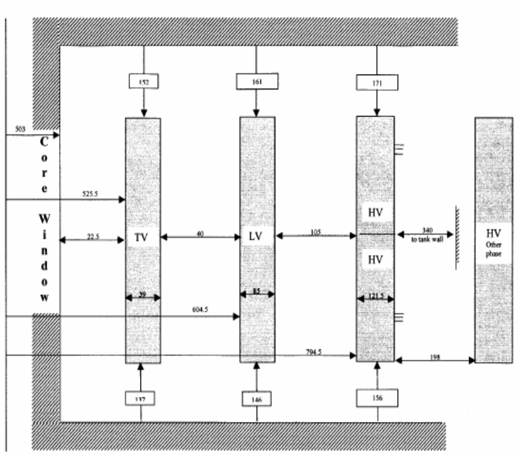
(a) Transformer model



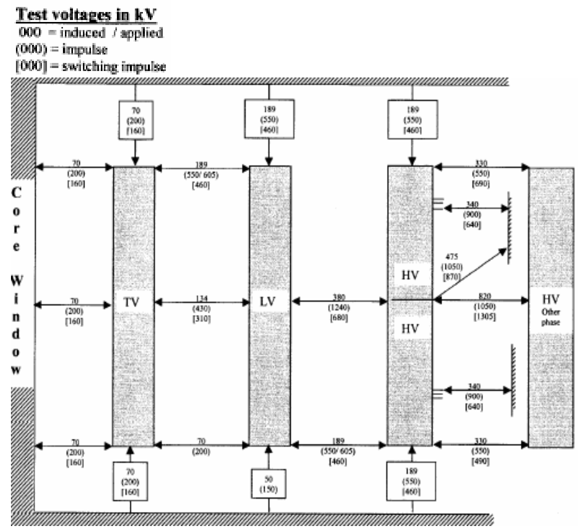
(b) FW- Impulse response at various nodes

FIGURE 12. Calculation of impulse voltage distribution in a transformer

Once the dielectric calculations (impulse, induce and A/C voltage) is done, the final insulation of the windings is done and is tabulated as shown below FIGURES 13 –a & b:



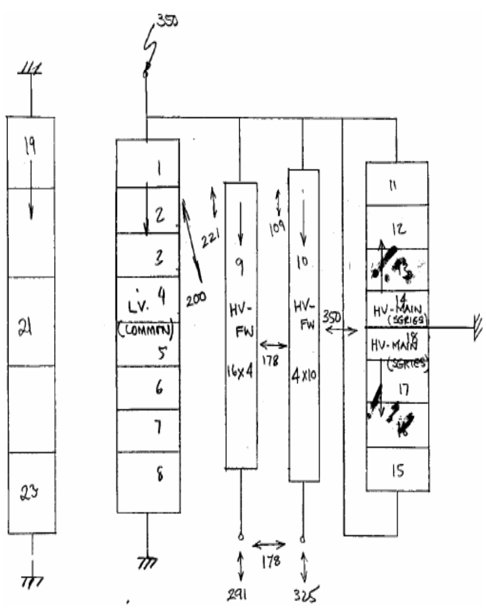
(a) elec./mech. clearances



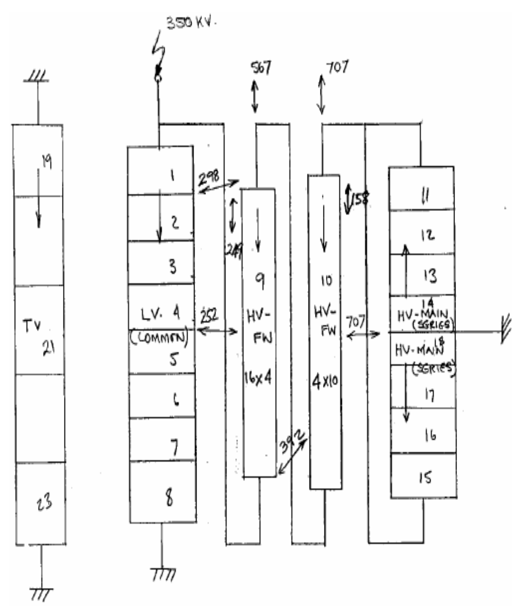
(b) calculated maximum voltage (induced/applied, impulse, switching impulse) stresses

FIGURE 13. Winding insulation design

To clarify the above, let us consider a example of an actual impulse study of an Auto-Transformer with grounded neutral & equipped with ± 5%NLTC & ± 10% LTC to regulate the HV side; 1) FIGURE 14 –a &b, FW-Impulse on LV side with HV at different tap positions and, (2) FIGURE 15 –a, b & c. FW-Impulse on HV side with HV at different tap positions.

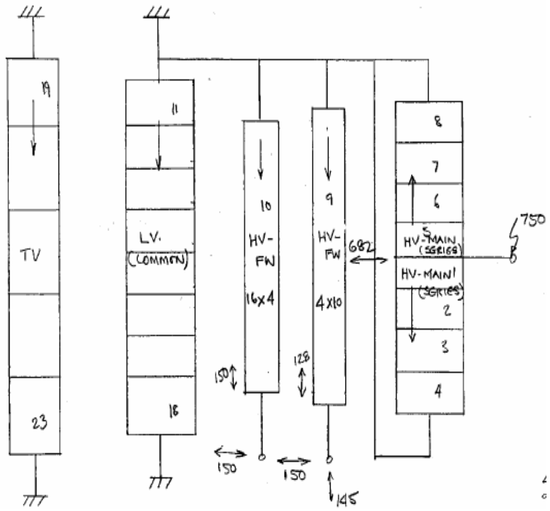


(a)

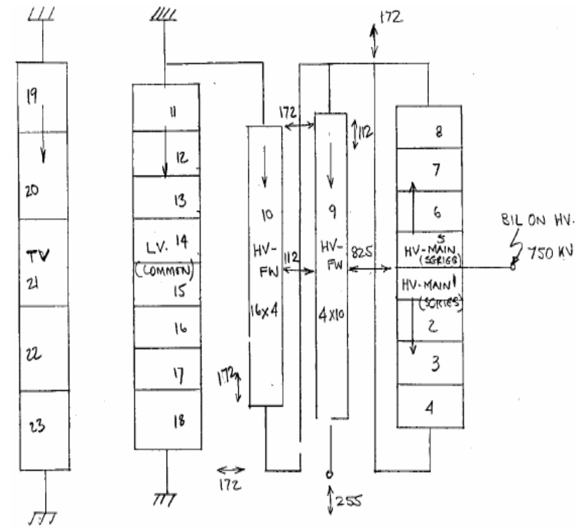


(b)

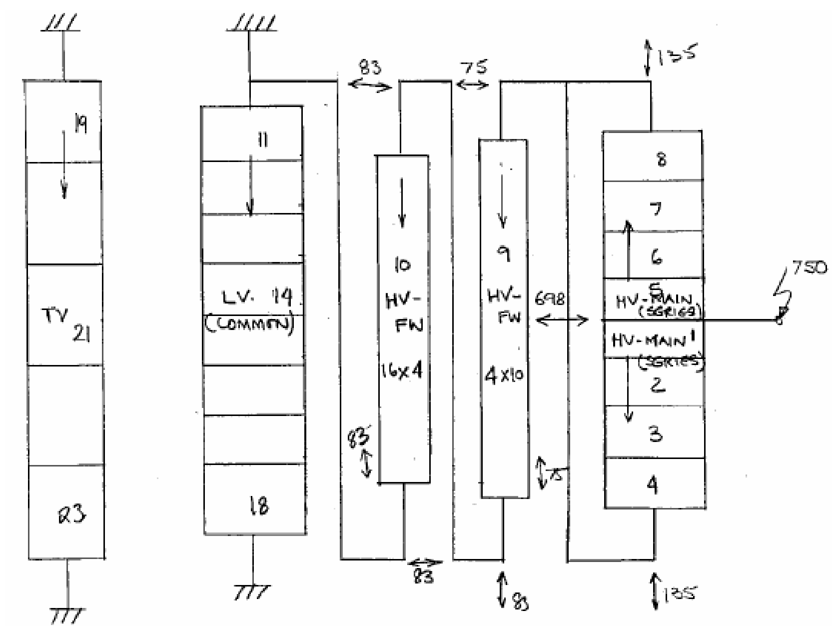
FIGURE 14. FW-Impulse on LV (common) winding with (a) HV (series) winding at minimum turns (b) HV (series) winding at maximum effective turns.



(a) HV(series) winding at minimum turns



(b) HV(series) winding at minimum effective turns



(c) HV(series) winding at minimum effective turns

FIGURE 15. FW-Impulse on HV (series) winding

It becomes very clear from the above example that the selection of the tap position(s) during impulse test is very critical for an Auto-Transformer.

For *external* protection of the Auto-Transformers, the following techniques can be implemented such that the amplitudes of the incident waves are reduced: 1) The right choice of distribution lines to avoid districts immune to heavy thunder-storms; 2) The use of overhead ground wires; 3) Proper insulation coordination which is mainly carried out by the use of lightning arrester installed at the substations (NOTE: The lightning arrester should not be switched off even when the line is disconnected).

VOLTAGE REGULATION OF AUTO-TRANSFORMERS AND ITS INFLUENCE ON IMPEDANCE

Auto-Transformers are equipped with no-load tap changers (NLTC) and/or load tap changers (LTC) for voltage regulation of HV and/or LV voltage, depending on the customer requirements. Voltage regulation of either HV and/or LV voltage can be achieved by providing tapings commonly referred as "***regulating winding***", either on the main body of the HV (series) and/or LV (common) winding or as a separate winding, with different possible geometrical location on the core leg with respect to other winding(s) on the same core leg and connected electrically to either series and/or common winding. Each of these possible combination(s) has it own influence on the design and on the impedance profile of the Auto-Transformer. **The provision of tapings in an auto-transformer, increases its equivalent size and hence its cost.**

The electrical location of the regulating winding would have influence on the type of design, i.e. constant flux design or variable flux design (each of which has its own merits and de-merits), and the geometrical location of the regulating winding would have influence on the impedance profile of the Auto-Transformer. (For a quick reference, please refer to FIGURES 18 thru 22.)

Electrical location: There are five possible practical solutions for the electrical location of the regulating winding FIGURE 16.

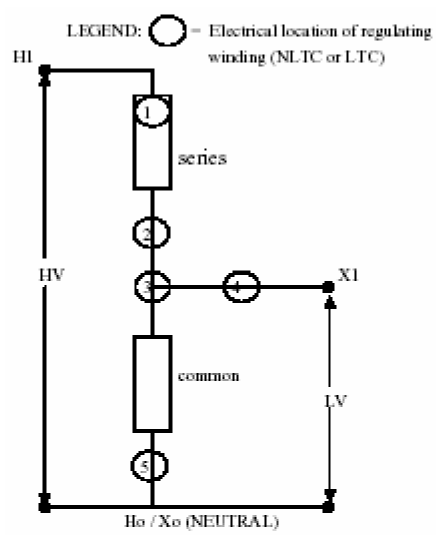


FIGURE 16. Possible practical electrical location(s) of the regulating winding (NLTC or LTC).

The above electrical locations of the regulating winding can be detailed as:

(1) In the main body of series winding
This is commonly done for NLTC application or for some rare cases of LTC when the number of step required is high (within the permissible limits of the short-circuit design), to regulate the HV voltage. This would result in a constant flux type design.

(2) As a separate winding, electrically connected to the series winding (above the auto point)
This is commonly done for NLTC and/or LTC application to regulate either HV or LV voltage. If used to regulate LV voltage then the design would be of variable flux type.

(3) In the fork of the Auto-Transformer connection
This is commonly done for NLTC and/or LTC application to regulate LV voltage. This would result in a constant flux type design.

(4) In the line end of the LV voltage
This is commonly done for LTC application or for some rare cases of NLTC (within the permissible limits of the voltage stress of NLTC), to regulate the LV voltage. This would result in a constant flux type design.

(5) In the Neutral end of the Auto-Transformer connection

This is commonly done for NLTC or LTC application, to regulate either the HV or LV voltage. Irrespective of the voltage regulated this would result in a variable flux type design.

NOTE:

1) Combination of 1 with 2, 3, 4 or 5 is often used (off-course demanded by customer specification). One such case would be when NLTC and LTC are used to regulate the HV voltage.
2) **For variable flux design, great care must be taken in the design as the no-load losses, tap step voltage, flux density in the core leg and the noise of the Auto-Transformer varies with the tap position. If a tertiary winding (discussed later) is required and brought out for use, a compensating series transformer may have to be provided to keep the tertiary voltage constant.**

In order to select the correct electrical location, the following aspects of the NLTC or LTC equipment and the regulating winding design should be considered:

For NLTC or LTC equipment

- Voltage to ground.
- Voltage across tap winding.
- Current through contacts.
- Step voltage.

NOTE: <u>All</u> of the above requirements must be within the permissible limits as outlined by the OEM of the NLTC or LTC.

For Regulating winding

- Number of turns per tap (this is critical for the winding design type).
- Protection (whether additional protection is required? such as zinc-oxides)
-

Geometrical Location: There are four possible practical solutions for the geometrical location of the regulating FIGURE 17.

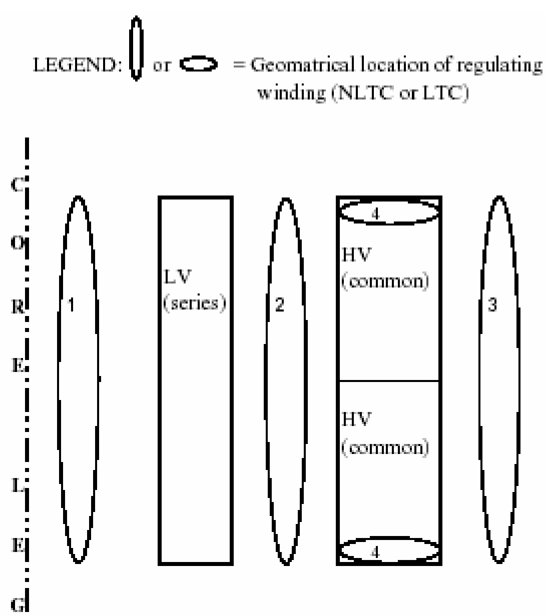


FIGURE 17. Possible practical geometrical location(s) of the regulating winding (NLTC or LTC).

The above geometrical locations of the regulating winding can be detailed as:

(1) Innermost diameter
This is common for regulating winding connected to the neutral end or the line end of the LV voltage of the Auto-Transformer.

(2) Between series and common windings
This is common for regulating winding connected to series winding or the line end of the LV voltage of the Auto-Transformer.

(3) Outermost diameter
This is common for regulating winding connected to series winding.

(4) In the main body of the series winding
This is common for regulating winding connected to series winding the Auto-Transformer.

NOTE: Any combinations of 1 2, 3, or 4 are possible, as dictated by the design requirements (off-course demanded by customer specification).

In order to select the correct geometrical location, the following aspects of the regulating winding design should be considered:

Regulating winding design

- Voltage between windings.
- Lead layout design.
- Impedance variation over the tap range.

NOTE: <u>All</u> of the above requirements must be within the permissible limits of the design criteria and the customer specification.

Below are some examples which will help clarify the above issues. All the plots are for values of % Impedance on the extreme taps compared with the value on the nominal tap.

LEGEND: R = regulating winding, P = parallel (common) winding, S = series winding, U_1 = HV voltage, U_2 = LV voltage, %Vcc = % Impedance & % $V_{1\text{ or }2}$ = % of HV or LV voltage

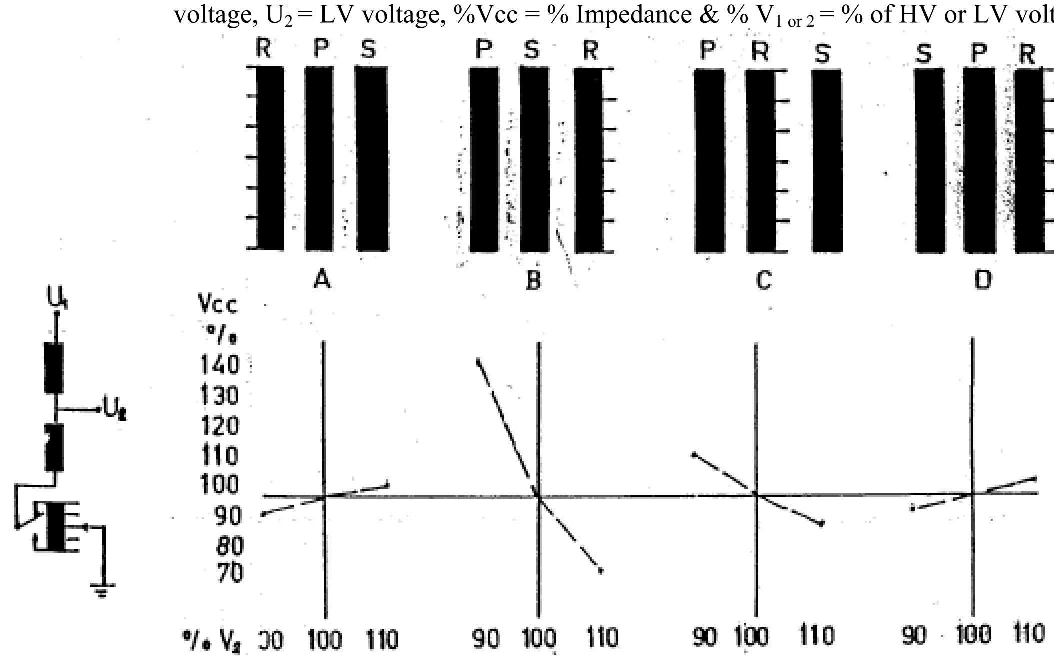


FIGURE 18. LV side voltage regulation with the regulating winding electrically connected to the neutral end of the Auto-Transformer (Auto-Transformer ratio 400 / 135 kV ± 10 %)

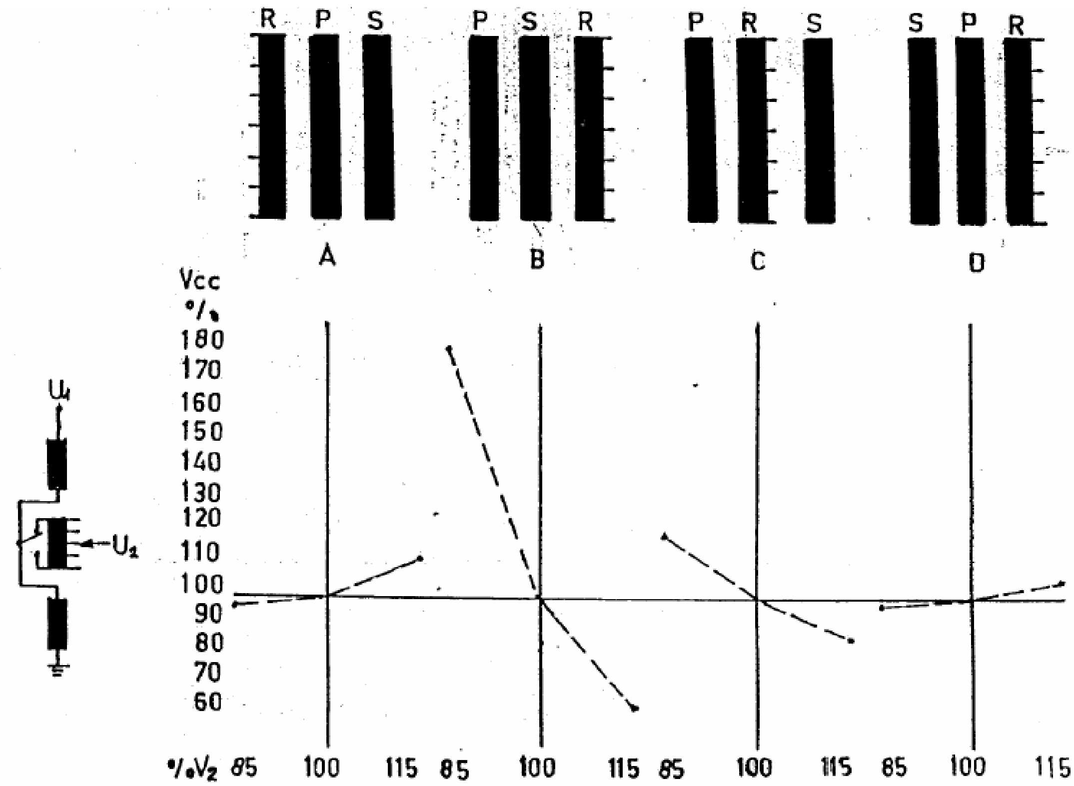


FIGURE 19. LV side voltage regulation with the regulating winding electrically connected to the line end of the LV voltage (Auto-Transformer ratio 400 / 135 kV ± 15%)

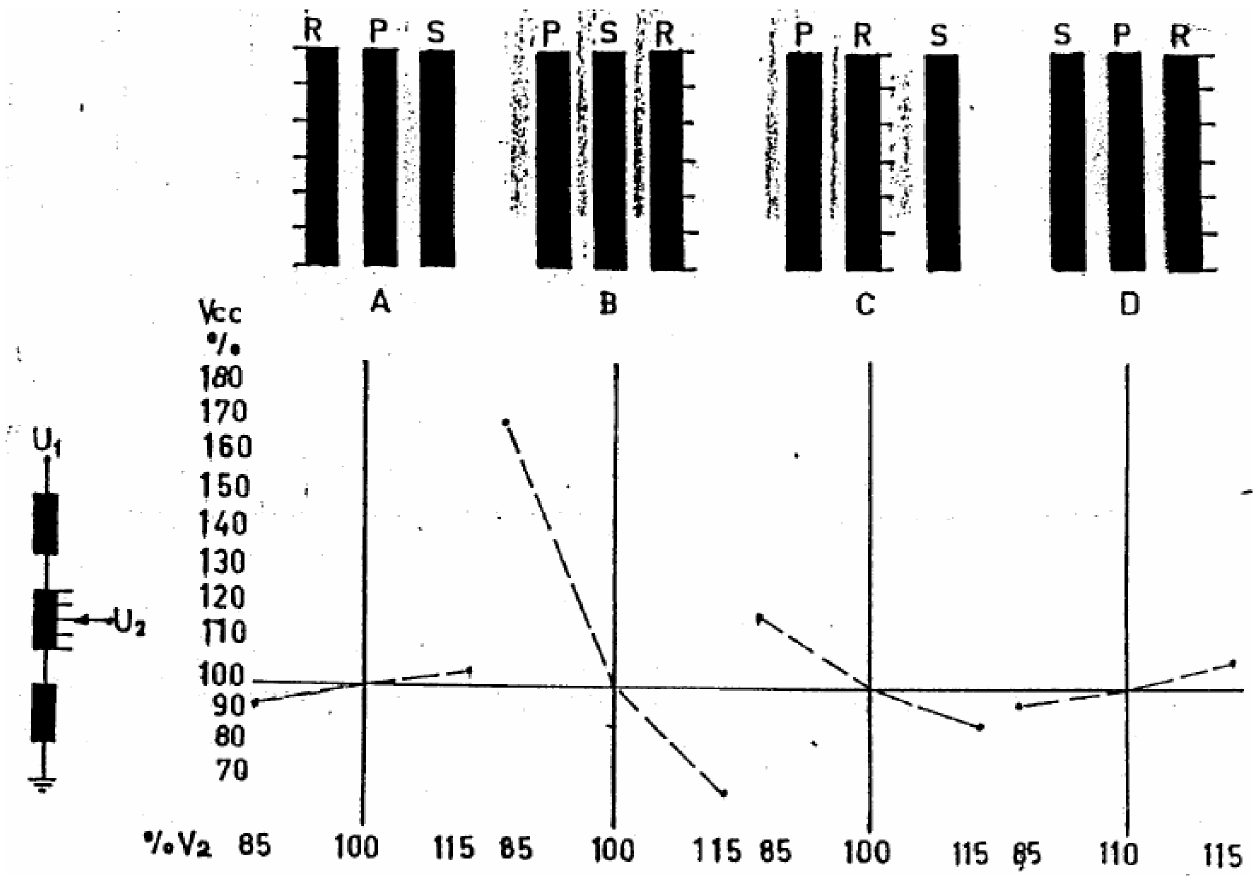


FIGURE 20. LV side voltage regulation with the regulating winding electrically connected in the fork of the Auto-Transformer connection (Auto-Transformer ratio 400 / 135 kV ± 15%)

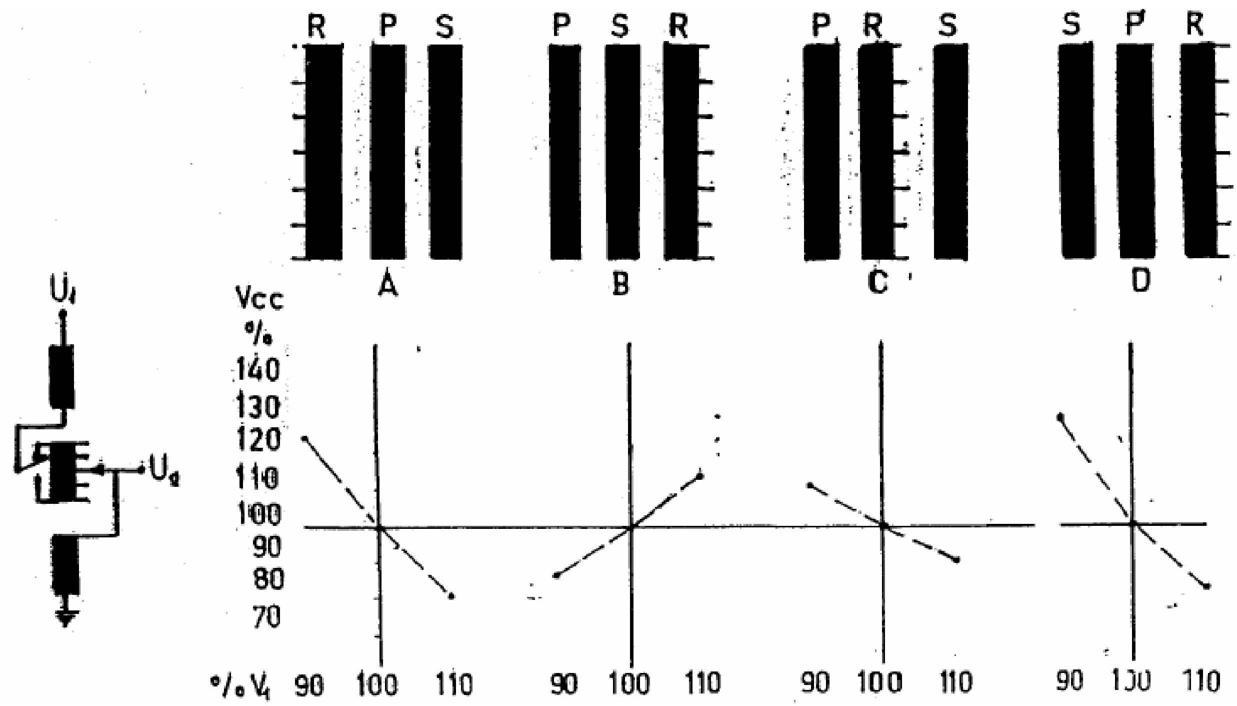


FIGURE 21. HV side voltage regulation with the regulating winding electrically connected in the series winding above the auto point (Auto-Transformer ratio 400 ± 10%/ 135 kV)

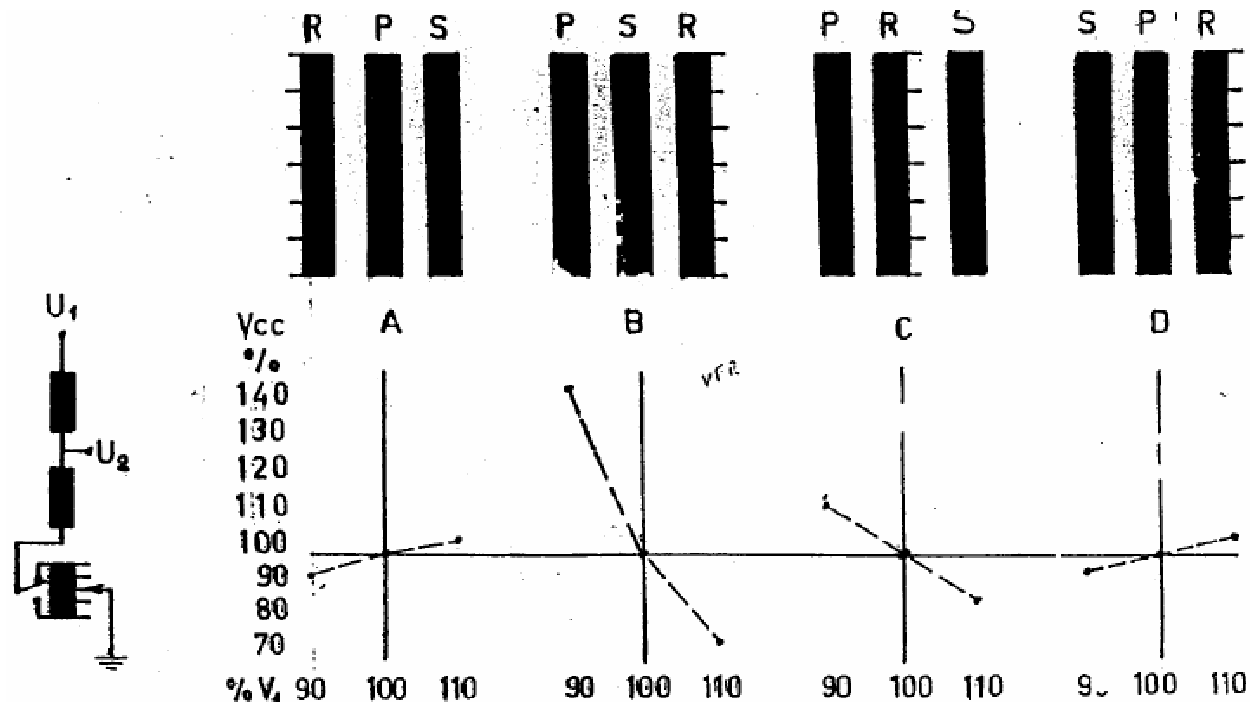


FIGURE 22. HV side voltage regulation with the regulating winding electrically connected to the neutral end of the Auto-Transformer (Auto-Transformer ratio 400 ± 10 % / 135 kV)

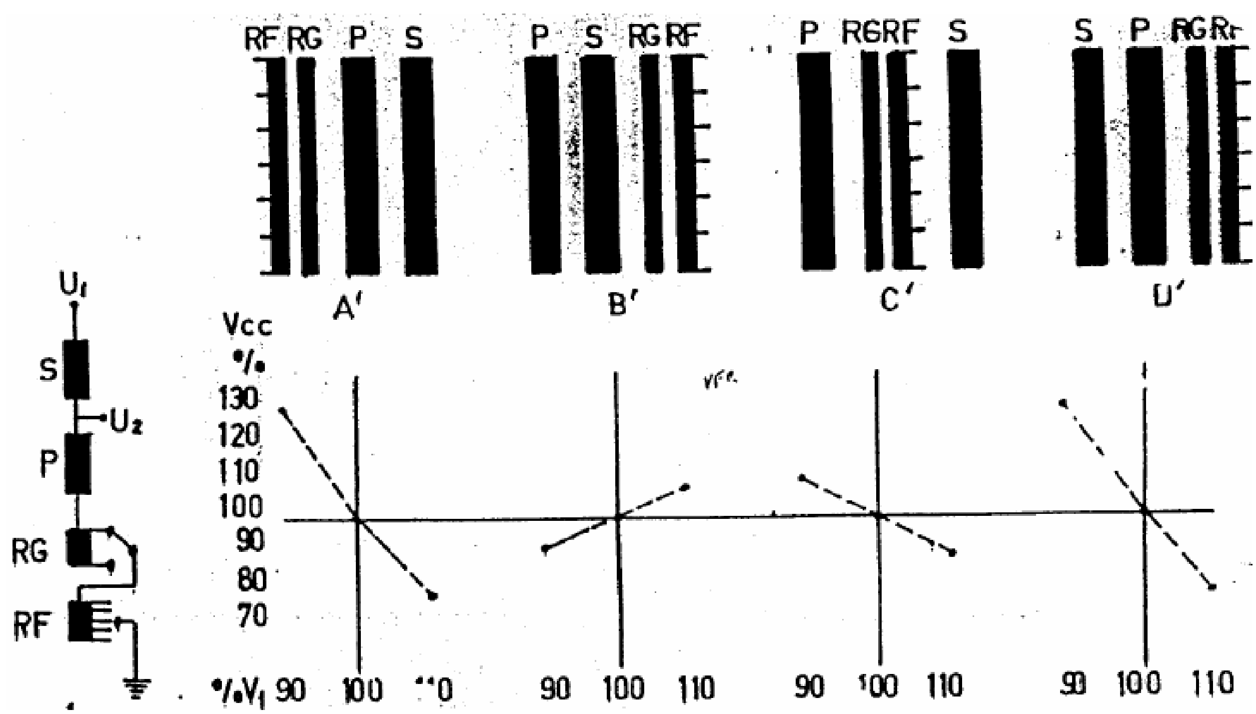
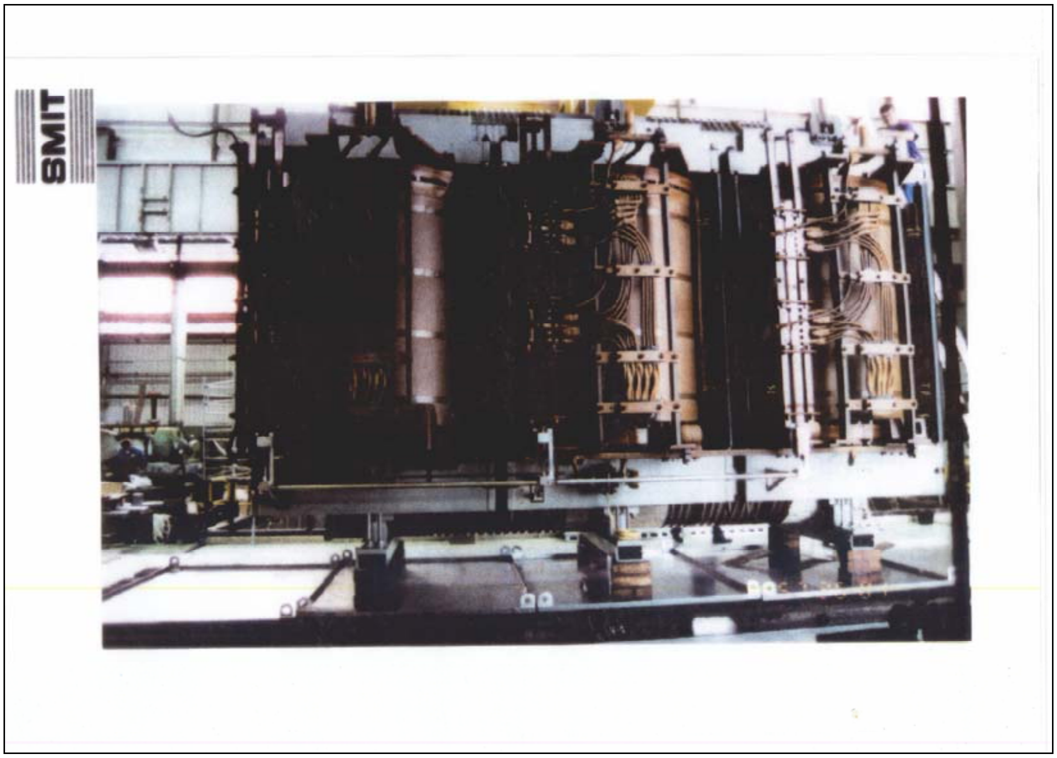


FIGURE 23. HV side voltage regulation with the regulating winding electrically connected to the neutral end of the Auto-Transformer with coarse-fine regulating windings “European style”
(Auto-Transformer ratio400 ± 10 % / 135 kV).

LEGEND : RG = coarse regulating winding & RF = fine regulating winding.

Pictures below show examples of the complexity of the lead design in a large auto-transformer as described above:



(a) NLTC leads

(b) LTC leads

Below is the comparison between regulating winding in, the neutral end (variable flux design) and in the 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

Three phase Auto-Transformers can have all the connections which the 2-winding transformer have, differing from them only by electrical connection of the windings.

Y- connected. This is the simplest and the most economical three-phase auto-transformer connection and hence most often used (the reasons are explained in a later section). Each leg of the three-phase is treated like a single-phase unit. FIGURE 24 shows the Y connected three-phase auto-transformer. Y connected auto-transformer (five-legged core form and shell form) suffer from the same short-comings as the Y-Y connected transformers, namely from the distortion of phase-voltages due to the fact that the zero sequence currents can flow along the return legs and induce zero sequence voltages), and to avoid this, delta connected tertiary winding is usually made use of or a three-legged core form (where the zero sequence flux cause losses in tank wall and in other metallic parts) design should also be considered. For **single–phase,** loading on considerable distortion of phase voltage takes place in the bank of single-phase (three-legged core form and shell form) units.

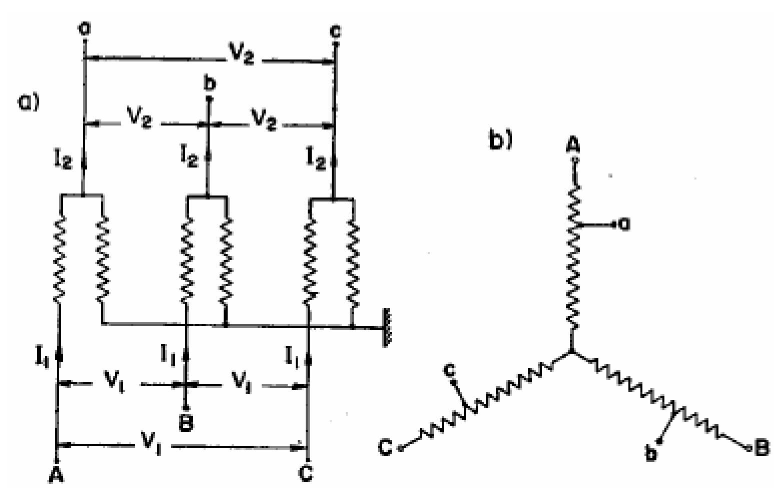


FIGURE 24. Three-phase auto-transformer with Y-connected windings

Delta connected auto-transformers (FIGURE 25) is rarely used as its co-ratio is larger than Y connected auto-transformer by about 1.16 to 1.73 times (for value of 1< k < 2). Obviously, if the numerical values of the voltages are the only consideration, delta connection is inferior to the Y-connection; but if phase shift is needed (as in case of "PST" **P**hase **S**hifting **T**ransformer) in addition to the voltage change, then the delta connection may be valuable. When a higher ratio than 2 to 1 is descried than the open delta-connection must be used.

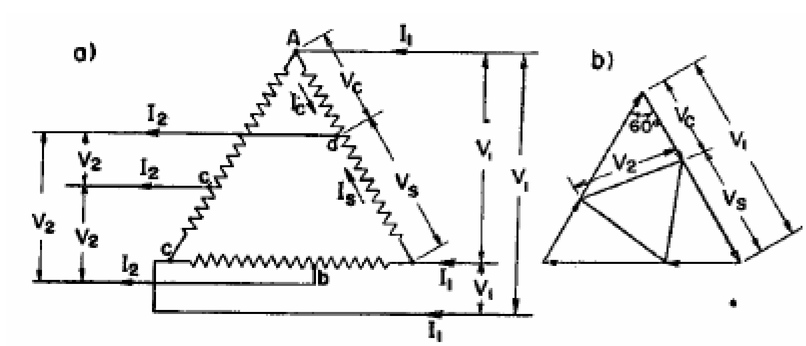
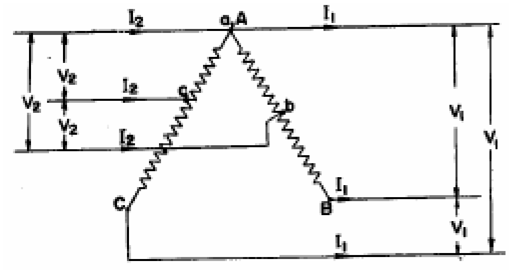
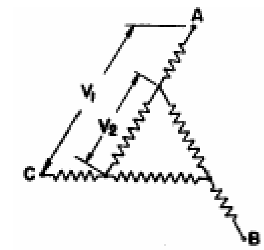


FIGURE 25. (a) Delta-connected auto-transformer and (b) its vector diagram

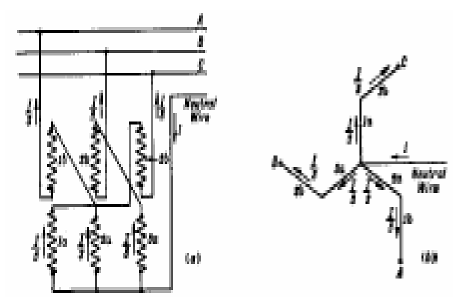
***Other connection*s**. The winding of auto-transformer can be connected in single zigzag, double zigzag, open-delta, in extended delta, in T-scheme and so on FIGURE 26



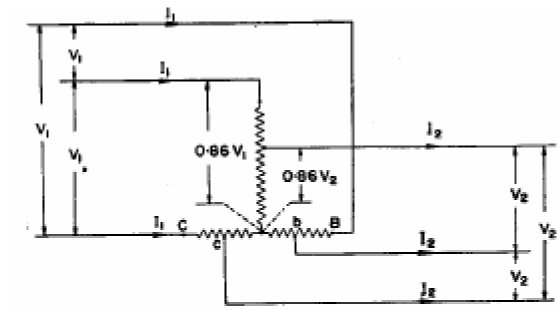
(a) Open Delta-connection



(b) Extended Delta-connection



(c) Single zigzag connection

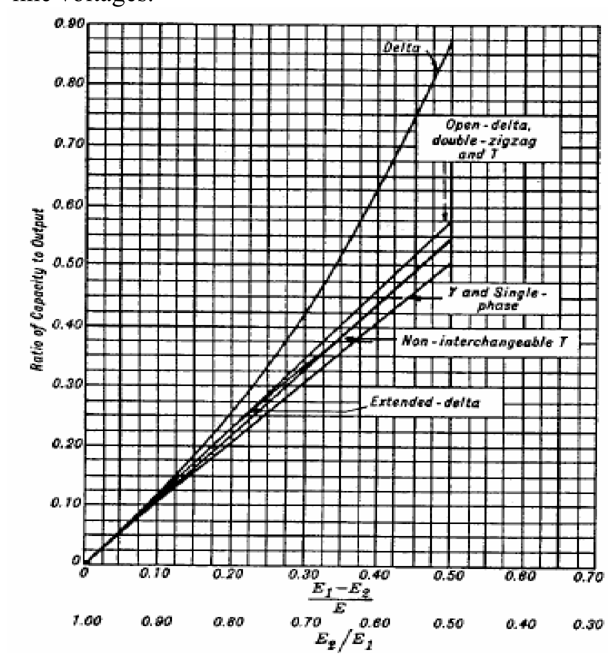


(d) T-connection

FIGURE 26. Other Connections

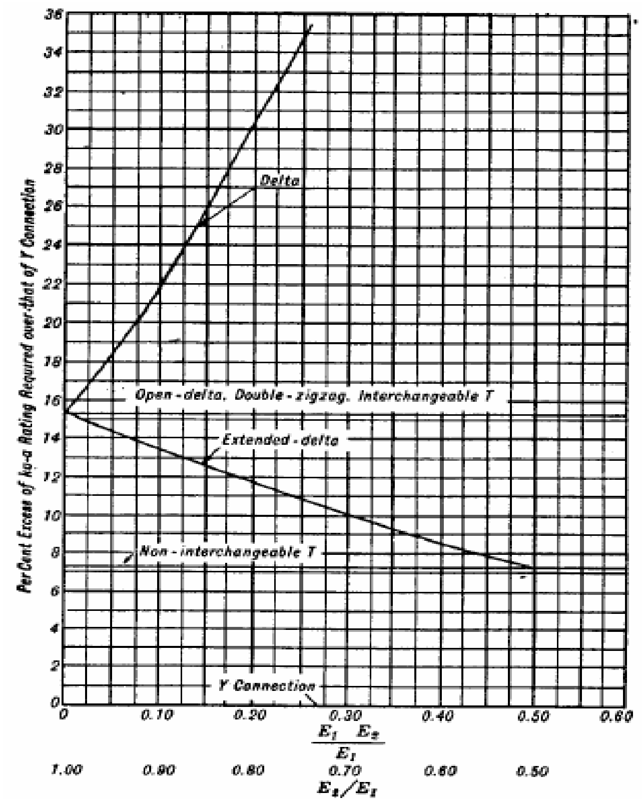
COMPARISION OF THE Y, ZIGZAG, DELTA, EXTENDED DELTA, OPEN-DELTA & T-CONNECTION

A comparison of relative kVA capacities required for these connections is given in the curves below, for various ratios of high and low line voltages.



Ratio of capacity to output of various auto-transformer connections

Although the relative economy is also seen in these above curves, a much better idea is obtained from the curves below, where using the Y connection as the standard, the excess kVA capacity required by the other connections is plotted against various values of the co-ratio. Assuming the co-ratio is equal to 20% (the ratio of low voltage to high voltage being 80%), the non-interchangeable T-connection requires 7.4% more kVA than the Y-connection. Next in economy is the extended-delta connection (11.8% more kVA capacity than the Y-connection); open-delta, double zigzag and interchangeable T-connection (each requiring 15.5% more kVA capacity than the Y-connection); and the least economical is the delta connection (requiring 29.7% more capacity than the Y-connection).



Capacity required by various auto-transformer connections compared with Y connection

Therefore Y-connection should be used whenever possible without trouble from the third-harmonic-voltage phenomena.

DELTA-CONNECTED TERTIARY WINDING IN Y-CONNECTED AUTO-TRANSFORMERS

Most of the customers specify delta-connected tertiary winding in all auto-transformers. But is a tertiary winding necessary in all cases?

Tertiary windings are provided for the following purposes:

(a) To supply auxiliary load.
(b) To suppress the third harmonic currents and voltages in lines.
(c) To stabilize the neutral point of the fundamental frequency voltages.
(d) To reduce the zero sequence impedance of the transformer to zero sequence currents flowing during fault conditions and unbalanced loading conditions.
(e) For power factor improvement by connecting synchronous condensers to the tertiary winding

If the tertiary is required to supply auxiliary load and power factor improvement than it is justified to have one; but, for other purposes outlined above, the tertiary winding in auto-transformers with solidly grounded neutral and three phase three-legged core form design **can be eliminated** under many of the system conditions. This topic on itself is so big; those interested in investigating this topic in detail can refer to the paper presented by me which can be made available upon request.

Tertiary winding when required must be sized and designed such that it does not become the weak link for the auto-transformer failure. Generally a rule of thumb of 35% (1/3) of the electromagnetic kVA is used to size the tertiary winding, but this may not be sufficient in some cases. The tertiary winding should be sized according to the fault current (taking the maximum value for various fault conditions) and or the actual loading on the tertiary winding which ever is greater.

When all the three windings (common, series & tertiary winding) are loaded simultaneously (for arithmetic loading or vectorial loading), the transformer windings should be so designed that under all operating conditions and possible fault conditions, the windings are not subjected to excessive over-loads. For arithmetic loading the calculation is simple, but for vectorial loading FIGURE 27 –a & b indicates division of an auto-transformer with tertiary load. Current I_T is the equivalent current flowing in the primary or the secondary circuit to balance the load on the tertiary circuit. The kVA rating of each winding can be calculated as shown:

Consider the case of step-up operation (FIGURE 27 (a)):

$kVAseries = \alpha * kVAprimary$

$kVAcommon = \alpha * kVAprimary * e^{j\theta H} + kVAtertiary * e^{j\theta T}$

where: θ_H = power factor angle of high voltage load

θ_T = power factor angle of tertiary voltage load

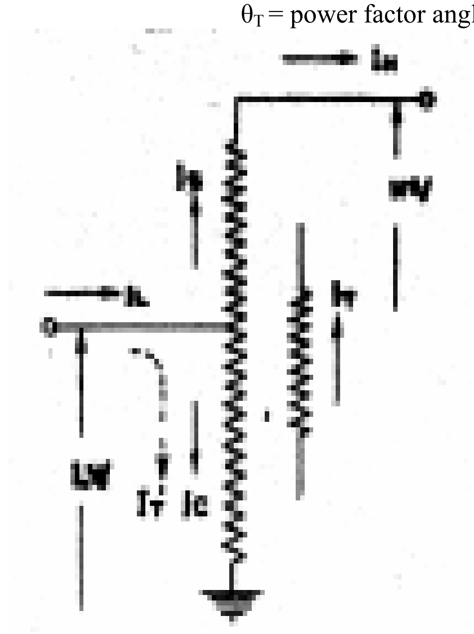


FIGURE 27 (a). Current division in step-up mode for auto-transformer with tertiary load.

By similar analysis for step-down operation, the kVA of the windings can be written as (FIGURE 27 (b))

$kVAseries = \alpha * (kVAsecondary * e^{j\theta L} + kVAtertiary * e^{j\theta T})$

$kVAcommon = \alpha * kVAsecondary * e^{j\theta L} - (1-\alpha) * kVAtertiary * e^{j\theta T}$

where: θ_T = power factor angle of tertiary voltage load

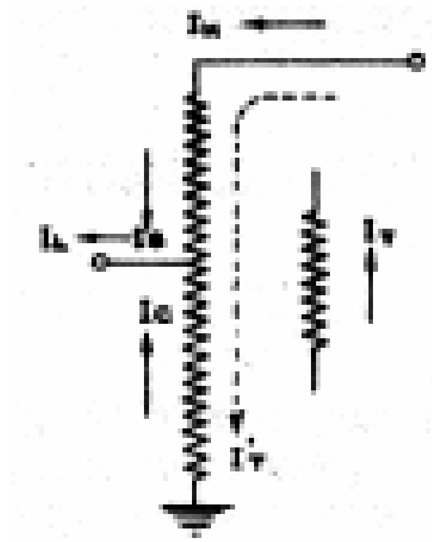


FIGURE 27 (b). Current division in step-down mode for auto-transformer with tertiary load.

From the above equation and FIGURE 27 (b), it shows that the current through the common winding is reduced when both low and tertiary circuits are loaded.

For loading conditions where the power is fed into the tertiary instead of being taken out, the above formulae will be modified to the extent that sign of kVA tertiary is reversed.

TESTING OF AUTO-TRANSFORMERS

For the most part, the testing of an auto-transformer is no different than the 2-winding transformer, except for impulse and heat-run testing.

In view of the above, for impulse testing the worst case tap position for each winding (this may differ from the ANSI standards) must be selected.

For heat-run test the maximum current (in all windings) tap (if provided) position must be selected (this may also differ from the ANSI standards).

CONCLUSION

Considerable cost savings can be realized by the use of auto-transformers (lower overall cost, lower total losses, lower size, better regulation, lower exciting current). By suitable winding arrangements, impedance variation with tap changing can be limited. Under many system conditions, the tertiary winding in a three-legged, three-phase Auto-transformer can be omitted; further realizing cost savings and reliability. When all the windings are loaded in multi-circuit auto-transformers, care should be taken to provide adequate winding capacity. By adopting the use of state of the art FEA programs, thorough study of the impulse and short-circuit behavior of the auto-transformers can be done, realizing optimum results in impulse and short-circuit protection of the auto-transformers. With all this in mind, it would be safe to say that Auto-transformers should be used every time when the application is available.

REFERENCES

[1] S.B. Vasutinsky "Principals, Operation and Design of POWER TRANSFORMERS".

[2] SMIT Technical documentation

[3] The late L. F. Blume, A. Boyajian, G. Camilli, T. C. Lennox, S. Minneci, V. M. Montsinger " A Treatise on the Theory,Operation, and Application of Transformers".