T A P S

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OBJECTIVES

- To raise awareness on how the taps' function in specifications influences transformer cost and operational requirements.
- To discuss economic factors and system needs that are to be considered in specifying taps' function.
- To highlight usefulness of different types of taps and tap changers.
- To pinpoint helpful role and limitations of standards in preparation of transformer procurement specifications.
- To know the dangers when taps are used different to their function stated in specifications.
- To familiarize a few design and manufacturing practices for tap windings.
- To create communications between users and manufacturers by which both can be benefited.
- To suggest future works.

OUTLINE

This tutorial covers taps in two winding power transformers in transmission stations. Taps in autotransformers are not covered as it will be an extensive subject and can easily be a separate tutorial. Taps in transformers at generating stations (main output, system service and unit service), phase shifting transformers, distribution transformers, regulators, mobile transformers etc., are also not covered in this tutorial.

Topics covered in this tutorial are:

---Guidelines in standards.

---Types of taps based on function and tap changer operation.

---Choice of electrical connection and physical location of taps.

---Effects of tap range and number of taps on transformers' first costs and on life cycle costs.

---Effects of tap range on regulation and overloads.

---Effect of taps on losses, impedance and short circuit currents.

---Taps in WYE and DELTA connected windings.

---De-energized and on-load taps.

---De-energized tap changers (DTC) and on-load tap changers (LTC).

---Reactor and resistor types of LTCs.

---Use of series transformers.

---Design and manufacturing practices for tap windings.

---Function of taps stated in purchasing specifications and how they are used in service.

---Suggestions.

---Conclusions.

STANDARDS

C57.12.10 suggests ±5% DTC taps in 2.5% steps in HV winding and ±10% LTC taps in 0.625% steps in LV winding. C57.12.10 is limited to two winding transformers up to 100 MVA, HV 230,000 volts and LV 36,230 volts. Many users often specify the above DTC taps in HV and LTC taps in LV irrespective of transformer type (auto, two winding etc.), MVA, HV voltage and LV voltage.

Consider a step-down transformer. Transformers designed with DTC and LTC tap ranges per C57.12.10 have to be checked for correct operation during input voltage (HV voltage) fluctuations. As LTC is on the output side (in LV) parameters such as core flux density, impedance, step voltage etc., will change when the input voltage changes. It will be helpful if the standards address the variations on transformer parameters and their effect on transformer operation. C57.12.10 states that LTC taps are to be in 0.625% steps, it would have been clearer if C57.12.10 had also stated that these taps are constant flux taps. Based on system requirements and to obtain economical and trouble free operational transformers, users need to decide whether to write transformer purchasing specifications to suit their systems or to specify the taps per C57.12.10.

Taps can be as classified as below.

1. Constant flux taps.
   - Voltage in any untapped winding is constant from tapping to tapping i.e. volts per turn remains constant throughout the tap range.

2. Variable flux taps.
   - Voltage in the tapped winding is constant from tapping to tapping i.e. volts per turn changes from tap to tap.

3. Mixed regulation or combined voltage variation taps.
   - A portion of the taps act as constant flux taps and the remaining portion of the taps act as variable flux taps.

Note: ANSI and many other standards require that cores are to be suitable for over fluxing by 10% (i.e. 110% voltage) at no load and 5% at full load.

Suggestion:

Least cost transformers can be procured if users verify whether guidelines for the taps stated in ANSI or other standards suit their system needs before adopting these guidelines in the standards as their purchasing specifications.

TAPS LOCATIONS AND FUNCTIONS

For two winding power transformers, taps can be categorized in to the following types based on their location and function.

1. Taps in HV for HV variation
When these taps are used to maintain LV voltage constant for fluctuations in HV voltage then flux density in transformer core remains constant at all tap positions. When load on transformer goes up, LV voltage falls depending on transformer impedance and load power factor. In this situation, with HV voltage remaining constant, if the taps are varied to maintain LV voltage constant, then flux density in transformer core and all the associated parameters like percent impedance, sound level, losses etc, will change. Users should be aware of the safe limits of these changes to avoid transformer operational problems.

2. Taps in LV for LV variation
When HV voltage is constant, flux density in transformer core will be constant at all tap positions. When these taps are used to maintain LV voltage constant for variations in load (MVA and power factor) then there will be no change in transformer core flux density. When HV voltage fluctuates, core flux density and all the parameters dependent on core flux density will change. Caution is required to operate the transformer under this condition. Based on the extent of variation in core flux density and other parameters, if it is safe to operate the transformer, then taps on LV can be used to maintain LV voltage constant for fluctuations in HV voltage.

3. Taps in HV for LV variation
These taps maintain LV voltage constant for changes in regulation. For constant HV voltage, core flux density will be different at different tap positions and will be maximum at minimum turns tap position. For proper operation of the transformer, users should be aware of the changes in other parameters (percent impedance, losses, sound level etc.) at different tap positions. If these taps are used to maintain LV voltage constant for fluctuations in HV voltage, then flux density in transformer core remains constant at all tap positions.

4. Taps in LV for HV variation
These taps maintain LV voltage constant for fluctuations in HV voltage. Flux density in transformer core is directly proportional to HV voltage. With no variation in HV voltage, at all tap positions flux density in the core remains constant.

5. Taps in HV for combined voltage variation
A portion of the taps maintains LV voltage constant for fluctuations in HV voltage and a portion of the taps maintains LV voltage constant for changes in regulation.

6. Taps in LV for combined voltage variation
Except that the taps are in LV, what is stated above for taps in HV will be applicable for these taps also.

CHOICE OF WINDING FOR LOCATION OF TAPS

(A) Based on system requirements:

1. In almost all transformers DTC taps are on HV side. In substation transformers HV is normally on input side. Magnitude of the input voltage depends generally on location of the transformer in the system; near a generating station, at tail end of the system etc. DTC tap changer position can be selected based on location of the transformer in the system. DTC taps will not keep the output voltage constant either for input voltage fluctuations or for load variations. Main reasons to specify DTC taps are that they are cheap compared to LTC taps and assumption that input voltage will be relatively constant at a given transformer location in the system.

2. If output (LV) voltage has to be kept constant for fluctuations in input (HV) voltage, then it is preferred to have LTC in HV winding. If output (LV) voltage has to be kept constant for load variations, then it is preferred to have the LTC taps in LV winding. In both of these cases flux density in transformer core will be constant at all tap positions. For a given tap range, in general, transformers with constant flux taps will be less costly compared to transformers with variable flux taps. With constant flux taps all tap steps will have equal voltages.

(B) Based on transformer design considerations:

1. Transformer design with constant flux taps is simpler and takes less time to design than with variable flux taps. This is mainly because with constant flux taps impedance at tap positions vary based on windings arrangement, where as with variable flux taps impedance at tap positions vary based on windings arrangement and also vary due to the change in volts per turn at these tap positions.

2. In substation transformers usually LV is the output voltage. So, taps in LV for load variation (LV variation) will be constant flux taps. When LTC is in LV winding then design is often governed by number of turns in the tapping winding. Some other drawbacks with LTC in LV winding are problems associated with high currents and few turns per tap. Advantages are step voltage will be small and Impulse voltage appearing across the tap range will also be small. To obtain same number of tap positions, by using reactor type tap changer number of tap leads can be reduced to almost half compared to resistor type tap changer. Comparisons of reactor type and resistor type tap changers are discussed in later sections. Use of a series

transformer gives more freedom in choosing number of turns per tap, but a series transformer will increase cost and losses. Based on LV current, tap range, number of taps etc, in certain cases variable flux design with LTC in HV winding will be economical.

3. In substation transformers usually HV is input voltage. So, taps in HV for load variation (LV variation) will be variable flux taps. When HV BIL is high or when the tap range is large, impulse voltage that appears across the tap range could be large and could force to use a costly tap changer. Compared to taps in LV, taps in HV give more freedom to have the taps in body of the main winding.

(C) WYE and DELTA connected windings:

1. In a WYE connected winding, neutral insulation level is usually lower than line end insulation level. This allows use of a less expensive tap changer if LTC is located at the neutral end. With taps at neutral end, voltage to ground and phase to phase voltage in the tap changer will be lower compared to taps at line end.

2. Taps in a DELTA winding can be either at middle of the winding or at corners of the DELTA (line end). When the DELTA is fed by a grounded WYE, taps at corners of the delta is not preferred. The reason is, if a line to ground fault occurs either in the tap changer or from the tap leads to ground or from the tapping winding to ground then short circuit current will be very large since transformer offers very little or no impedance to limit the fault current.

3. For same MVA and voltage ratings if windings are connected in DELTA instead of in WYE, then winding current will be lower and number of tap turns for the same tap range will be larger. Due to these reasons, in certain situations, taps in a DELTA winding will be economical compared to the taps in a WYE winding.

Suggestion

During preparation of specifications, it will be beneficial to users if they consult with transformer manufacturers regarding choice of location for taps based on their requirements.

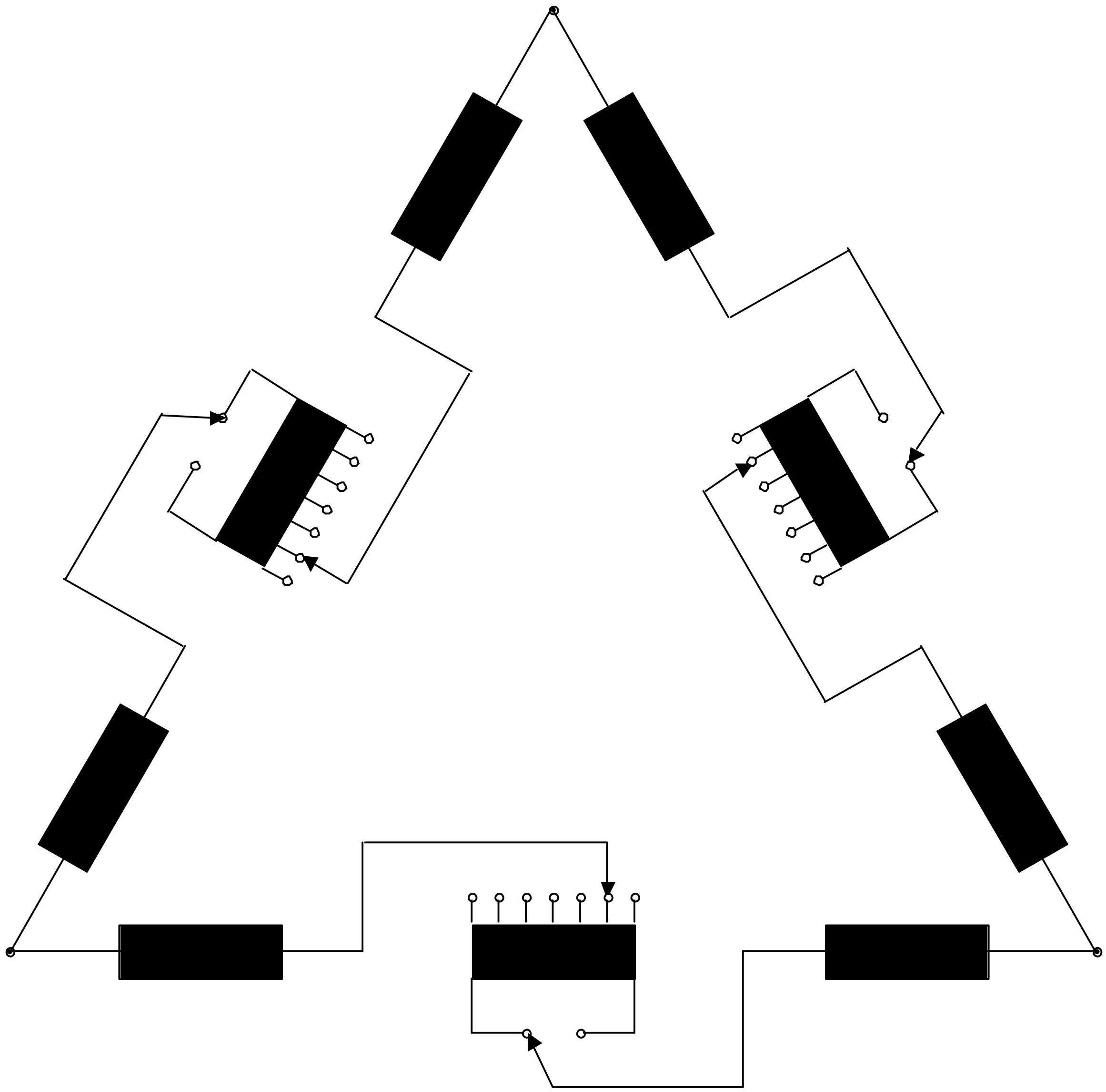


Figure 1: Taps at Center of Delta Winding

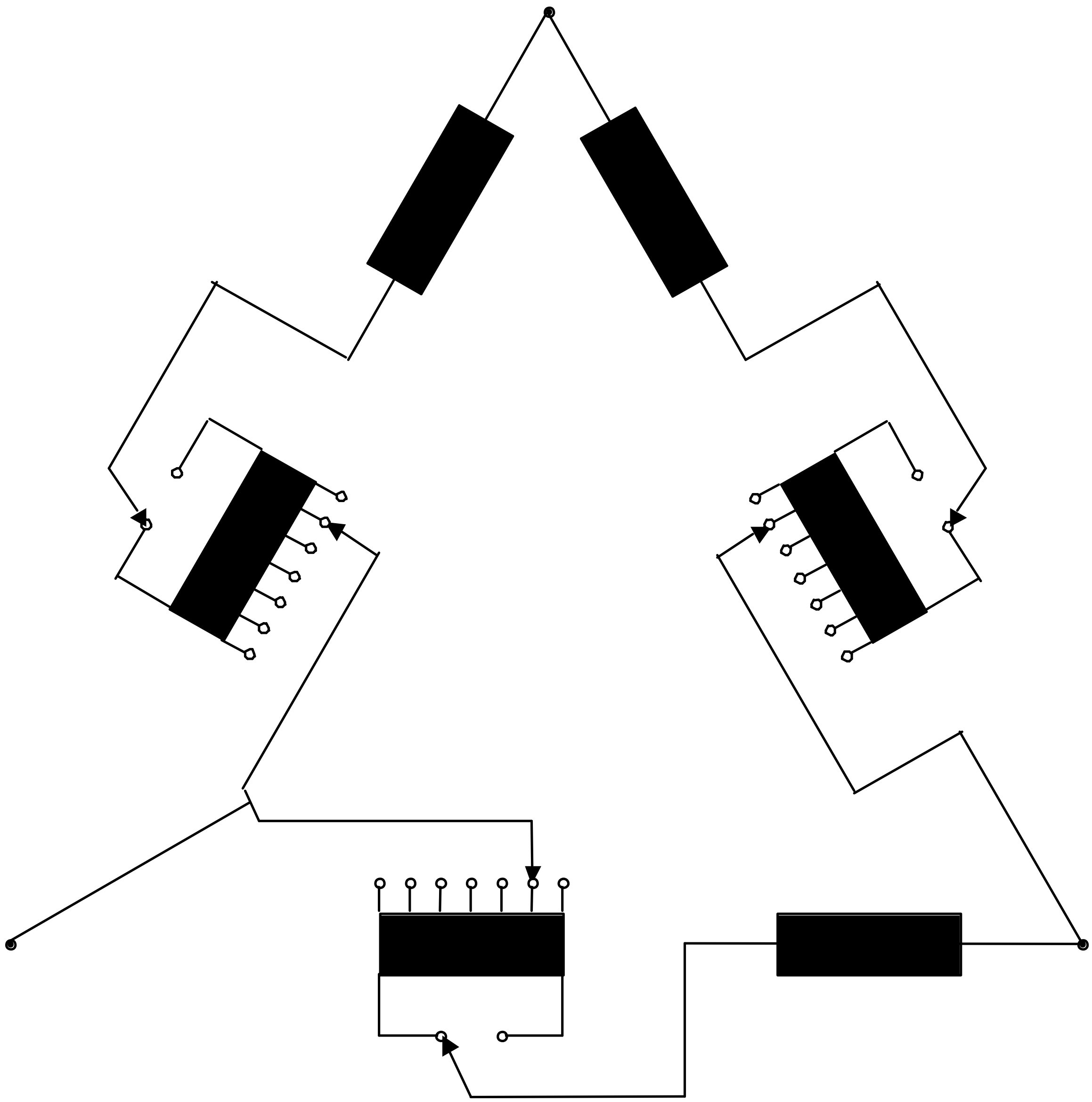


Figure 2: Taps at Corners of Delta Winding

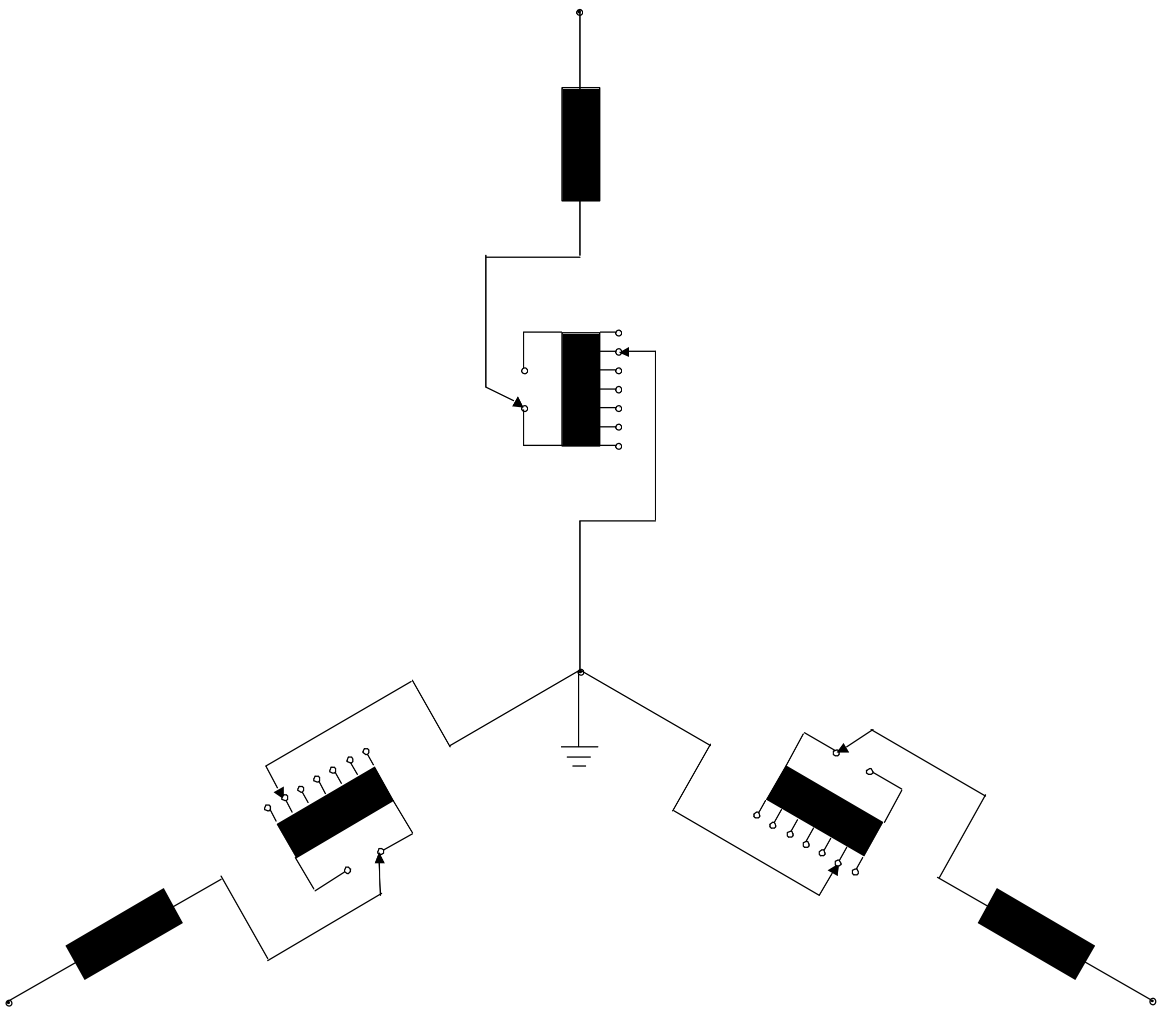


Figure 3: Taps at Neutral of Wye Winding

PHYSICAL LOCATION OF TAPS

When LTC is for reversing taps then tap winding must be a separate winding. When LTC is for linear or coarse/fine taps, then taps can be in body of the main winding if design and economics permit.

Usually DTC taps are linear taps and tap range is not normally large (e.g. $\pm$ 2x2.5%). As such it is common to have DTC taps in body of the main winding. When DTC taps are designed as reversing taps then the DTC taps must be a separate winding.

Typical physical locations for taps or tap winding are listed below.

1. Between core and LV winding.
2. Between LV winding and HV winding.
3. Outside HV winding.
4. In body of the main winding (at the ends, at the center etc.,).

A few reasons for choice of location for taps and tapping winding are given below.

1. When LTC taps are in LV winding for LV variation and are of reversing type, then placing the tapping winding between core and LV winding gives a compact and economical design. In this case variation in impedance across the tap range will be small.

2. When LTC taps are in LV for LV variation, it is not common to have the tapping winding between LV and HV windings or outside the HV winding. These arrangements are used when a specific swing in impedance across the tap range is required or for a special reason.

3. When taps are in HV for HV variation and the taps are reversing LTC taps then it is common to have the tapping winding over the HV winding. With this arrangement swing in impedance across the tap range will be small.

4. When taps are in HV for HV variation and the taps are DTC taps then it is common to have the taps in body of the main winding. When design and cost permit, LTC linear or coarse/fine taps can be in body of the main winding.

5. If short circuit forces and impulse voltage stress permit then in many cases having the taps in body of the main winding will be economical compared to a separate tapping winding.

Suggestions

1. Users to provide flexibility to manufacturers to adopt linear or coarse/fine or reversing LTC taps so that the taps or the tapping winding can be located at the most economical location.

2. Specifying impedance values at extreme tap positions in specifications is advisable.

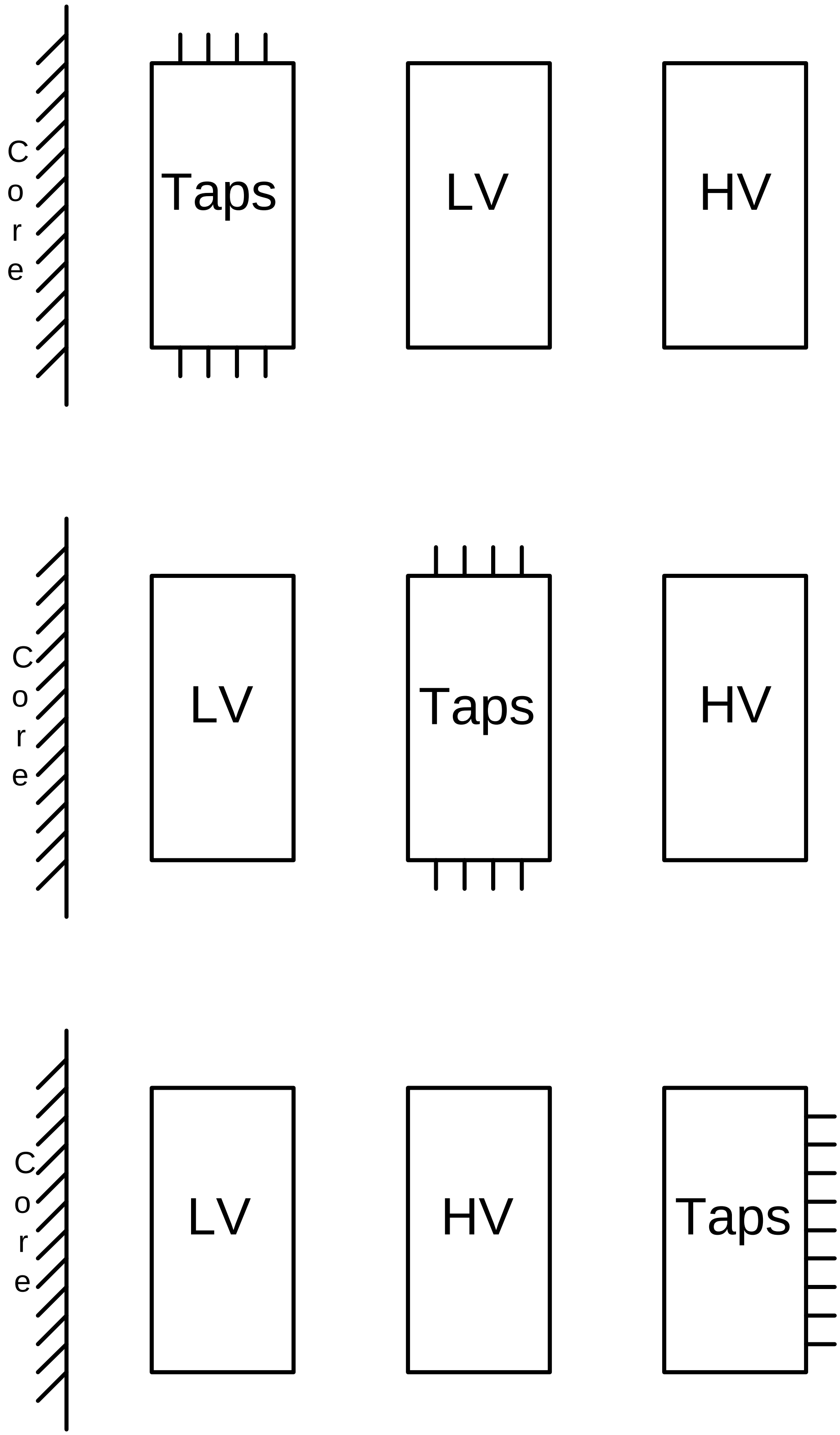


Figure 4: Different Physical Locations for Separate Tap Winding

VARIATIONS IN DTC TAPS

Three different variations in DTC taps are:

1. Bridging.
2. Linear.
3. Reversing.

In general, DTC taps are either bridging or linear type. Usually these taps are in body of the HV winding. No current will be flowing in the tap sections that are not in the circuit. So, amp-turn distribution in HV winding changes from tap position to tap position. Amp-turn distribution is more uniform at maximum turns position. At minimum turns position all tap sections will have zero amp-turns. It is preferred to balance HV and LV amp-turns to reduce short circuit forces.

1. **Bridging**

Bridging type taps are simple and widely used when taps are in body of the main winding. They are simple in construction and economical. Five and seven positions tap changers are very common. If more positions are needed, tap changers can be connected in series or special tap changers can be used. When taps are in two locations in body of the main winding then double bridging type tap changers can be used.

Main disadvantage of bridging type taps is the break or the gap in middle of the tap turns. When impulse voltage strikes the line terminal, large voltage appears across this gap. Magnitude of the impulse voltage that appears across the gap is a function of type of the main winding (disc, partial interleaved and fully interleaved), tapping range, type of tapping sections (interleaving sections or normal discs) and location of the tap gap from the line end. It is common practice to connect non-linear discs (zinc oxide discs) across the taps to control impulse voltage that appears across the tap range and the tap gap.

Tap gap in HV winding will affect the amp-turns distribution in LV winding. Tap sections in HV can be balanced by having larger turn pitch in LV at the height corresponding to HV tapping sections.

2. Linear

When linear type taps are used at ends of the coil, then no break or gap in tap sections is required thus resulting in cost savings. Linear type tap changers are little more complex and costly than bridging type tap changers. If this type of taps are used inside the main coil (not at the ends) then a tap break is necessary and this tap break has to be designed for the impulse voltage that appears across this break. Whether linear type taps are at ends of the main winding or inside the main winding proper amp-turn balance in LV winding is required to control short circuit forces.

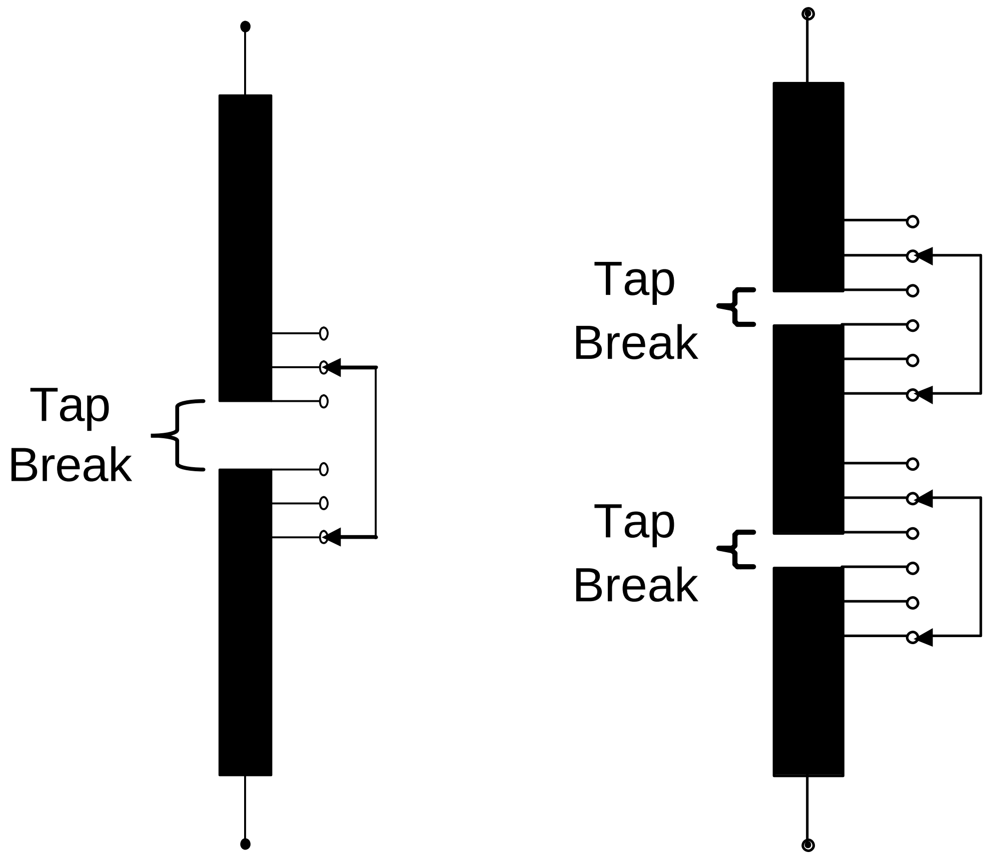
3. Reversing

When total tap turns are large or in special applications, reversing DTC taps are useful to reduce total tap turns to half. Number of tap leads is also reduced to half. Disadvantages of reversing DTC taps are:

(i) Requires a special tap changer or special connection of two normal tap changers.
(ii) At minimum turns position, load loss is increased due to the contribution of losses by all the tap turns.
(iii) Must be a separate winding.

Suggestion

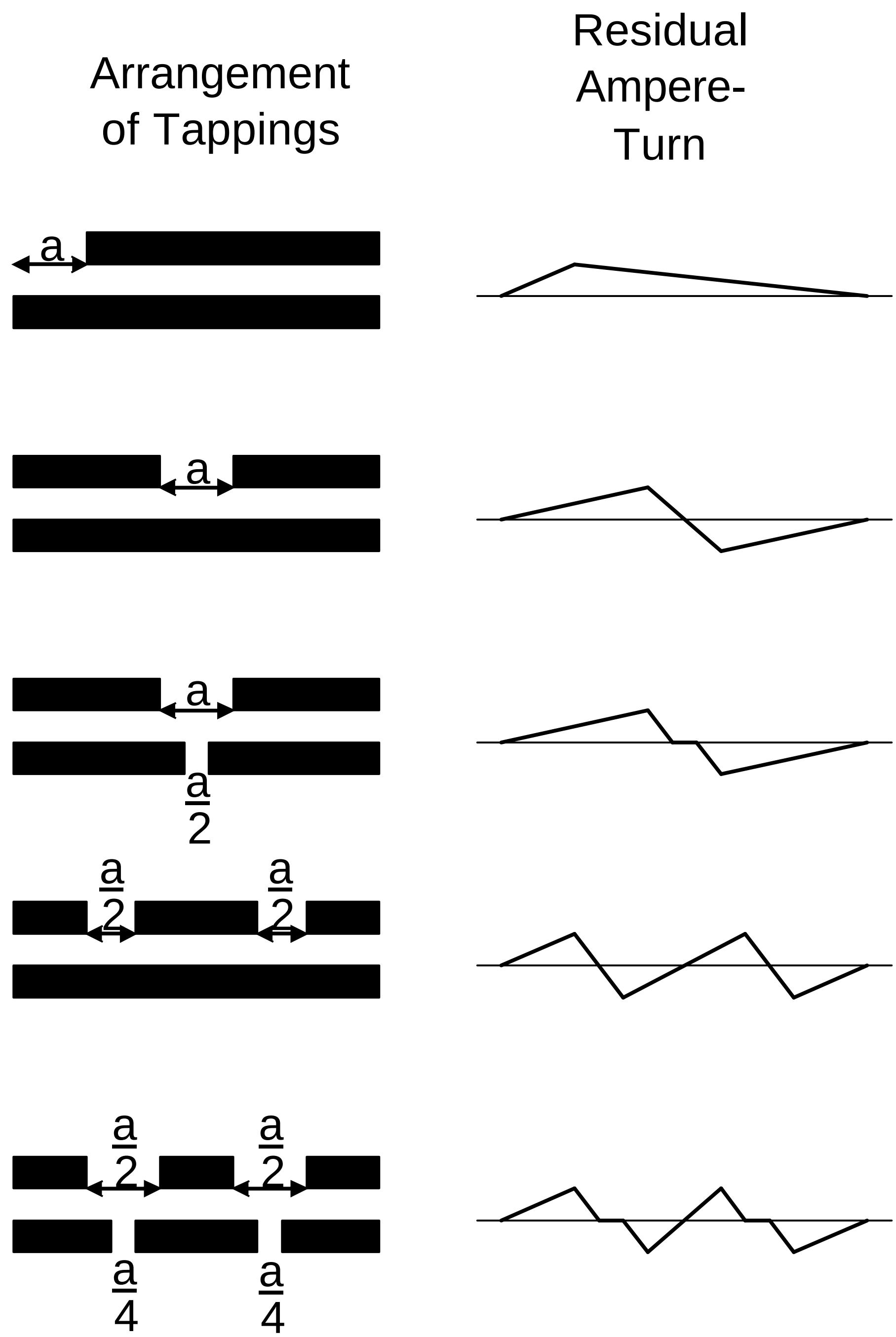
Before specifying both LTC taps and DTC taps, users should consider to eliminate DTC taps. If needed and to be economical, LTC tap range can be increased.



(a): at middle of coil

(b) at ¼ and ¾ height of the coil

Figure 5: Bridging Type Taps



a in HV : Tapping sections axial length

a in LV : Balanced axial length

Figure 6: Arrangement of Tappings in the body of Main Winding and their effect on short-circuit forces

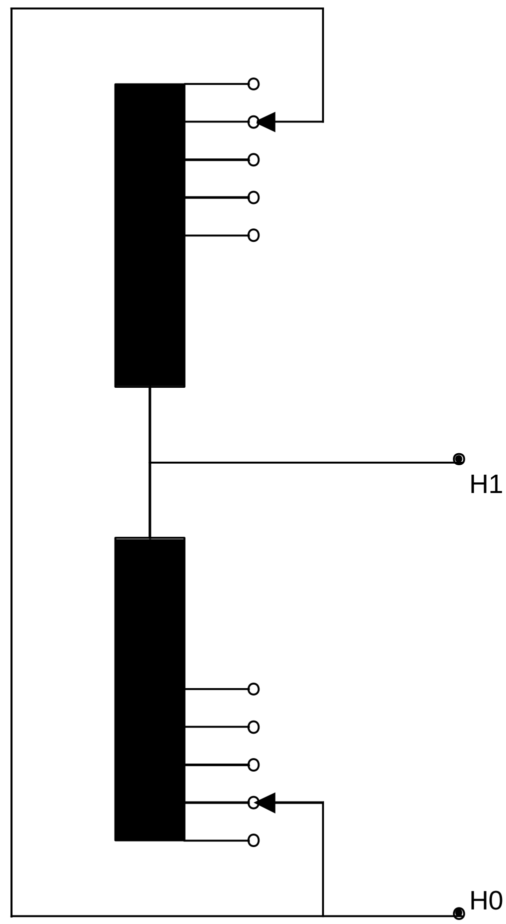


Figure 7: Preferred Linear Taps Arrangement

In Body of Main Winding

VARIATIONS IN LTC TAPS

The three different variations in LTC taps and a few reasons for choice of type of LTC taps are described below.

1. Linear

Linear taps are simple to design and also economical. With commonly available tap changers maximum number of linear taps that can be obtained are 17. When tap range is large and when more steps are needed, linear taps are not suitable. Another disadvantage is that for the same number of tap steps, linear taps will have more leads (about twice) compared to coarse/fine or reversing taps. If design and costs permit, linear taps can be located in body of the main winding.

2. Coarse/Fine

A transformer with coarse/fine taps will have lower life cycle cost compared to a transformer with reversing taps. This is due to lower losses for the taps below normal. Lower losses permit use of smaller coolers. For comparison two 83MVA, 115/28KV transformers were designed for the same no-load losses and same load losses at normal tap and with the same impedance. One design was with reversing taps and the other design was with coarse/fine taps. It was noted that the first costs for both the designs were almost same (below 1% difference) whereas load losses on minimum tap for the transformer with reversing taps was 28% more than that with coarse/fine taps.

Maximum of 34 tap steps only can be obtained with the commonly available reversing type tap changers. Multiple coarse/fine taps allow many more taps. Based on MVA and impedance if short circuit forces are not high, then coarse/fine taps can be located in body of the main winding.

3. Reversing

Reversing taps make designs less complicated compared to coarse/fine taps. A reversing tap winding can be easily placed between core and LV winding, between LV winding and HV winding or outside the HV winding. However reversing taps are not suitable for use in body of the main winding.

Suggestions

1. If users specify LTC tap range and number of taps but not the type of taps (linear, reversing etc), then transformer manufacturers can adopt the most economical type and offer transformers with least life cycle cost.

2. For economical operation, load losses at taps other than the normal tap are to be considered in evaluating the tenders.

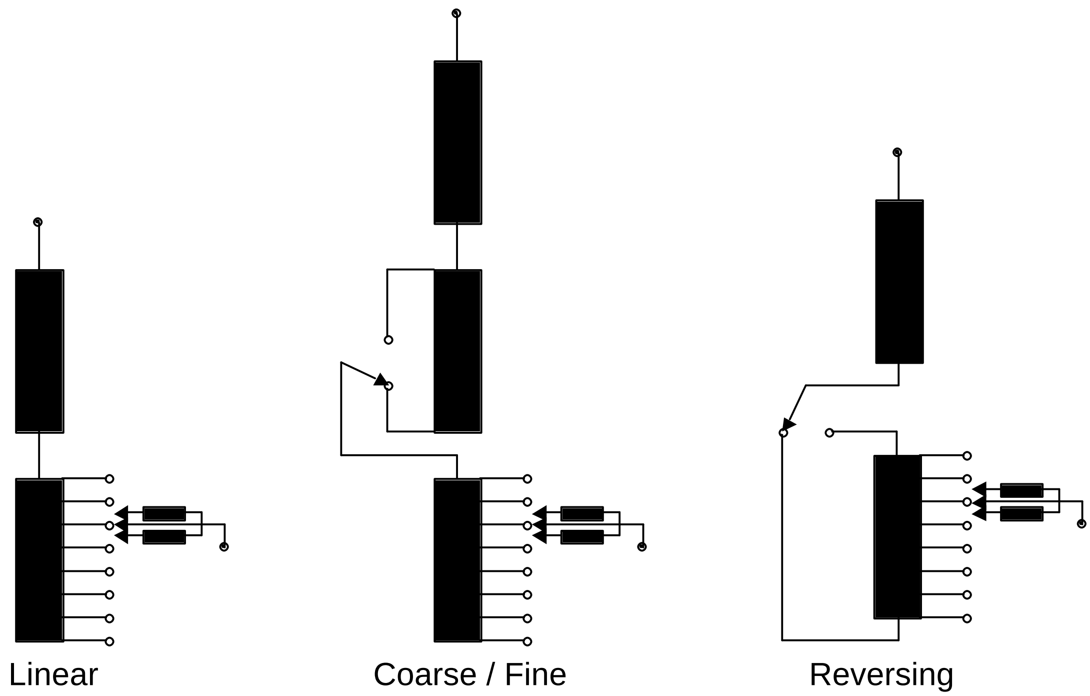


Figure 8: LTC Types

LTC TAP RANGE & TAP STEPS

When LTC tap range is increased transformer cost will go up. In many specifications there is no correlation among tap range, regulation and input voltage fluctuation. Often voltage specified on the maximum tap with taps in input winding, is much higher than the maximum system voltage. In a few specifications voltage specified on the minimum tap is very low compared to the system voltage. When tap range is large, it may not be economical to have taps in body of the main winding. For a given number of taps, any increase in tap range will increase percent voltage per tap. An increase in step voltage and interrupting KVA could force to choose a more costly tap changer. If number of taps is increased to limit the tap step voltage, then cost will increase. An increase in tap range will often increase short circuit forces. This effect is more dramatic in variable flux designs due to large variation in impedance. With a reactor type tap changer, if the step voltage is higher, then the preventive auto size will increase. If users are aware of the effects of above factors on design, then they can purchase optimally priced transformers matching to their systems.

Most specifications state that transformers should be capable of overloading per C57.91 but often information per clause 9.7 of C57.91 is not included in the specifications. In many cases the tap range is not large enough to compensate for regulation during overloads.

When LTC is in LV and LV voltage is small (say below 13.2KV and WYE connected), then number of turns per tap will dictate the design unless a series transformer is used. In such cases it is suggested that users check with manufacturers to determine the economics of shifting LTC on to HV side.

If users are familiar with the tap changers that are available then it will help to specify the tap range that makes the tap winding design simpler. Often users call for same tap range and same number of taps they had purchased many years ago. Users must be aware that many reputable manufacturers who had built these transformers had also built their own tap changers but some of these companies are now out of business. In some cases same type of tap changers are not available any more. Parallel operation of new transformers with these old transformers is possible with minor limitations, if any. Users should provide some leeway to manufacturers by not demanding identical transformers to the obsolete ones.

Suggestions

1. If users wish to reference the guide C57.91 in their specifications, then complete information per clause 9.7 of this guide should be included in the specifications.

2. At the time of preparing specifications, consultation with transformer manufacturers on tap range, number of taps etc, will assist users in procuring economical transformers which meet all system needs.

TYPES OF ON-LOAD TAP CHANGERS

Resistor Type

During tap changer operation resistors are connected for a short time across a tap to limit the bridging current and to maintain continuity in the power supply. There are several manufacturers for resistor type tap changers and each manufacturer has many models. This allows the freedom to choose a tap changer that matches the transformer design and also meeting all of the system requirements. Single phase resistor type tap changers with high current ratings (above 2500Amps) are available. When high phase to phase BIL (550KV and above) with in LTC is required (example: LTC at series end of a 500/230KV autotransformer), then single phase resistor type tap changers can be used.

Main disadvantages of resistor type tap changers compared to reactor type tap changers are number of tap leads is almost double and turns per tap must be whole turns. As these type of tap changers do not have vacuum interrupters, shorter inspection intervals are needed. On-line filters are normally used to keep the oil clean and to reduce the inspection intervals.

Reactor Type

The biggest advantage of reactor type tap changer over resistor type tap changer is that between two adjacent taps, voltage can be equal to volts per turn multiplied by half turn i.e.½, 1½, 2½ etc. This is achieved by bridging the tap with a reactor (preventive auto). Another advantage is that number of tap leads are almost half of that of a resistor type tap changer. Use of vacuum interrupters permit longer inspection intervals, high contact life and keeps oil clean.

Disadvantage of reactor type tap changer is that it needs a preventive auto. In bridging position preventive auto losses are added to the load losses. Preventive auto takes additional space inside the transformer and additional connections are required. Gapped cores are typically used in the preventive auto resulting in additional noise.

Tank mounted

Total requirement of oil and space for transformers with tank-mounted tap changers are in general lower than transformers with in-tank tap changers. Almost all reactor type tap changers are tank mounted. Only a few resistor type tap changers are tank mounted. Due to the limited space available, connecting the tap leads to the tap changer terminals of tank mounted tap changers is not always easy. Some specifications specify a particular type of tap changer (tank mounted or in tank) in their specifications. Best return for the investment can be obtained by selecting the type of tap changer (tank mounted or in tank) based on transformer life cycle cost and maintenance cost.

In-tank

Almost all in-tank tap changers are of resistor type. In-tank tap changers are available in a large number of types and ratings. They provide more flexibility in choice of their location (at end of the tank, between windings etc.,) and arrangement (three single-phase tap changers in same plane, in a triangle etc.). Thus routing of tap leads is easier compared to the tank mounted tap changer. When tapping winding current is large, then in certain transformers two three phase in-tank tap changers can be used by coupling their drive shafts together. With this arrangement considerable brazing or crimping on tap leads can be eliminated. Tap changers provide needed paralleling and there is no need to make parallel connections of the tap leads. Such a cost saving arrangement is not possible with tank mounted tap changers.

On power transformers regular inspection of in-tank LTC selector contacts is not required, as number of operations in a given time is not high like in a furnace transformer. Personnel trained to maintain tank mounted tap changers can maintain in-tank tap changers also with a little assistance from tap changer manufacturers.

Suggestion

Users should allow manufacturers to select resistor or reactor type tap changer and also tank mounted or in-tank tap changer based on technical and economical considerations.

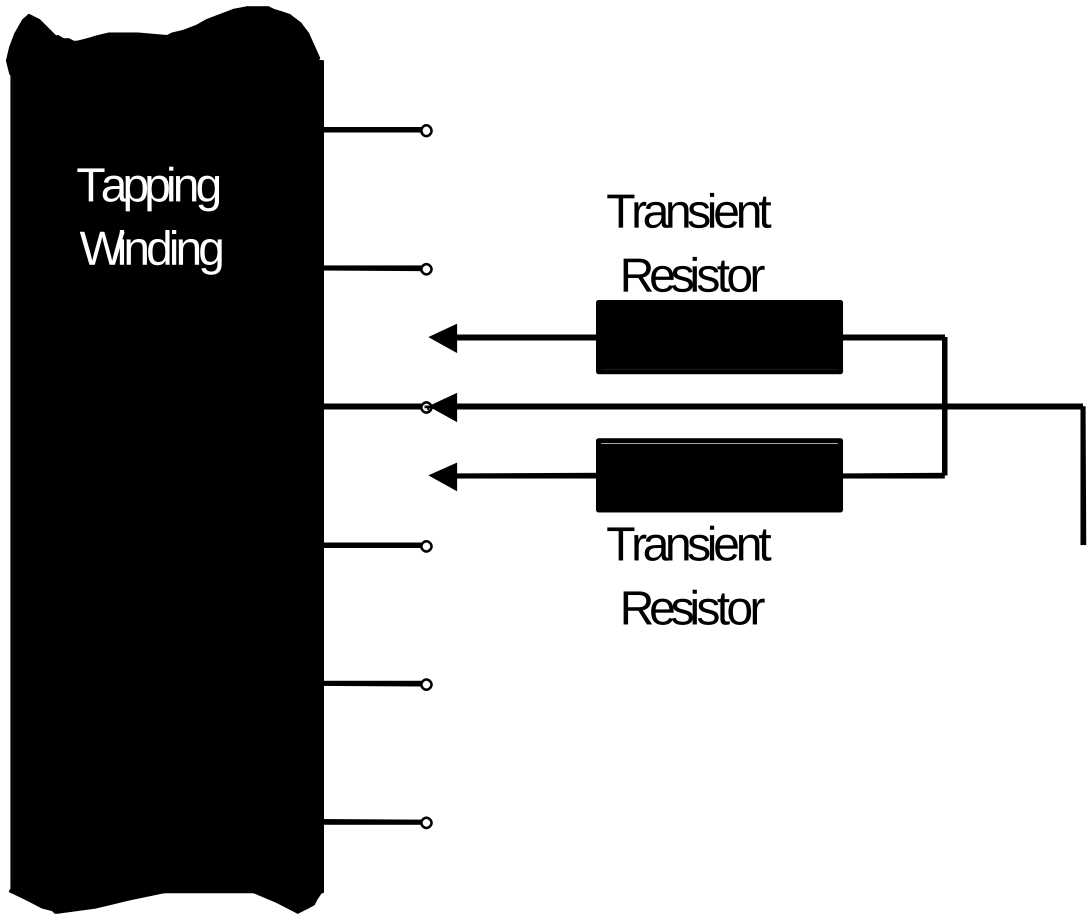


Figure 9: Resistor Type

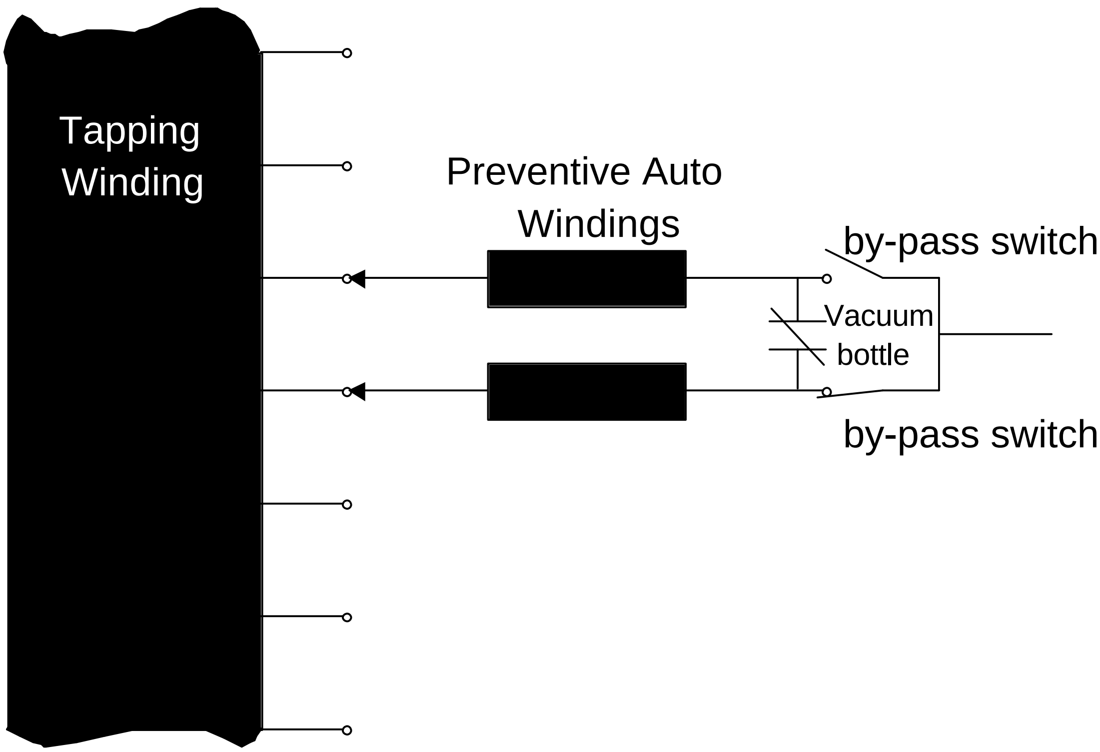


Figure 10: Reactor Type

TAP WINDINGS

A few types of commonly used tap windings are described below.

Helical

This type of winding is normally used when design permits to have all taps in one layer and when it is economical. Joints are made between tap leads and winding conductor. This winding is convenient to use as an inside winding. To minimize short circuit forces, this winding is wound in two halves and connected in parallel. Labor hours to wind this type of winding are higher compared to a multi-start winding because tap leads have to be brazed during the winding. Also because one portion of the winding is wound in left to right direction and the other portion is wound in right to left direction. Twice as many joints are required because the winding is in two halves. Both halves of the winding are paralleled outside the coil. Special care should be taken that tap leads coming from inside the winding have sufficient cross-sectional area and are properly cooled to avoid problematic hot spots. For economy, some manufacturers assemble or wind the tapping winding and the next coil outside it eccentrically. In such cases thickness of each vertical duct stick should be exact so that the coils are firmly supported. Due to the joints in the winding this type of winding is not recommended at high leakage flux areas (ex. between LV and HV windings).

Multi-start

This winding can be used in high leakage flux areas also as all the joints will be outside of the coils. Turns per tap is one of the deciding factors in selecting this type of winding. Often this winding is used when the tapping winding has to be between LV and HV windings. This type of winding is used as an inside winding under LV winding or also as an outermost winding over HV winding. When used as an outermost winding, ends of the winding must be properly anchored to avoid unraveling of the coil. In general series capacitance of this winding is large compared to helical or continuous disc windings. This large series capacitance will improve impulse voltage distribution in the winding and will reduce impulse voltage that appears across the winding. Normally, voltage of two taps appears between two adjacent conductors. Paper covering on winding conductors and gap between adjacent conductors must be properly chosen. By adopting special versions of multi-start winding, in many cases it is possible to avoid high voltage between adjacent conductors. Another disadvantage of multi-start winding is that pitch of the winding is normally high. Due to this, lead span should be properly controlled and end collars have to be correctly designed to have proper pressure on the coil. In this type of winding, as each tap spreads almost the whole height of the main coils, there will be good amp-turn balance at each tap position.

Connection of multi-start winding leads is critical. If the leads are connected on face of the coil, amp-turns in these leads will be highest at one extreme tap position. If these amp-turns are large this could cause extra losses and problematic hot spots in end frames, tank etc. Shielding is one way to avoid these harmful effects.

Another method of connecting the tap leads is to route them up to the tap changer and connect them on the tap changer. If the leads are near iron parts and amp-turns of the leads are high, then problematic hot spots and extra losses will occur in iron parts.

When design permits, it is possible to have special types of multistart windings to avoid the above undesirable effects.

Disc

This type of winding can be used as a separate tap winding or taps can be in body of the main winding itself. When taps are in body of the main winding then it is preferable to avoid joints in the winding. If joints are not made properly then there will be overheating and also dielectric problems. There are many ways to wind the tap discs to avoid joints in body of the winding.

Disc winding gives the flexibility to place taps at ends of the main coil or in the middle or in any other location in body of the main winding. Bridging type or linear type DTC taps can be located in body of main disc winding. Linear or coarse/fine LTC taps can also be located in body of the main disc winding. A different winding conductor than the main winding can be chosen for the tap discs. This is done either to bring the taps out without any joints or to reduce eddy losses and hot spot temperature in the tap discs.

If the disc winding is used as a separate tap winding, the winding is usually the outer most winding. This will facilitate to bring out the tap leads easily. When the main winding is DELTA connected, having the tap winding as the outer most winding is convenient to bring out the tap leads and to connect the taps in the middle of the delta. When the main winding is WYE connected with reduced impulse level at the neutral, having the tap discs winding as the outer most winding allows a lower phase to phase clearance.

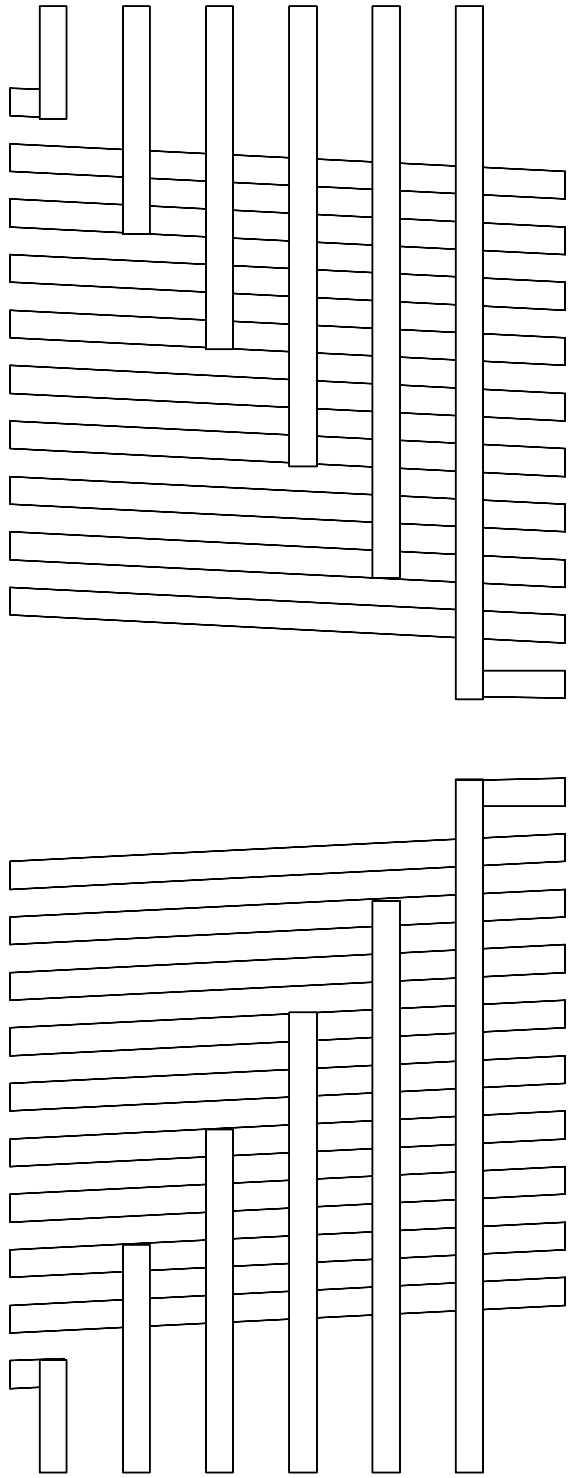


Figure 11: Tapped helix Winding

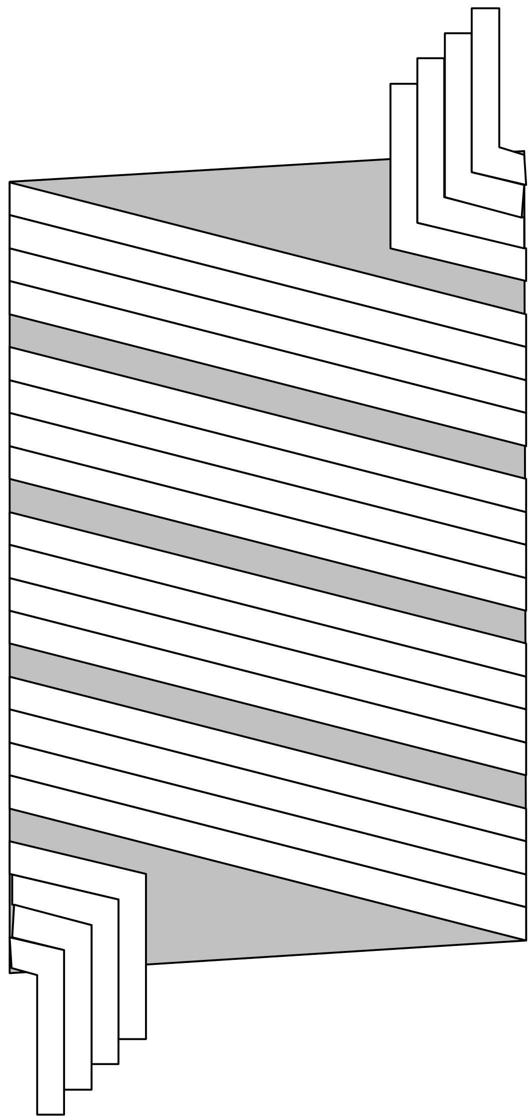


Figure 12: Multi-start Winding

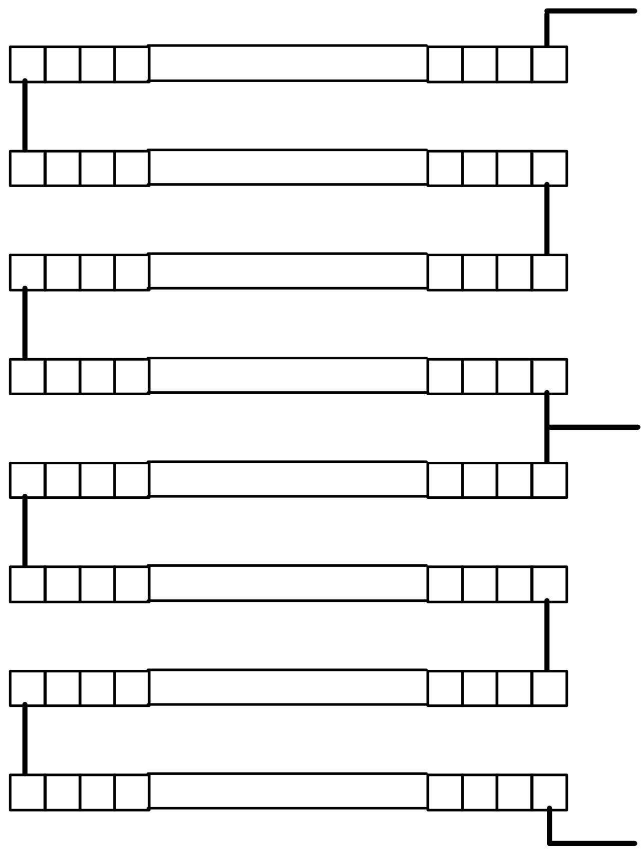


Figure 13: Disc Winding

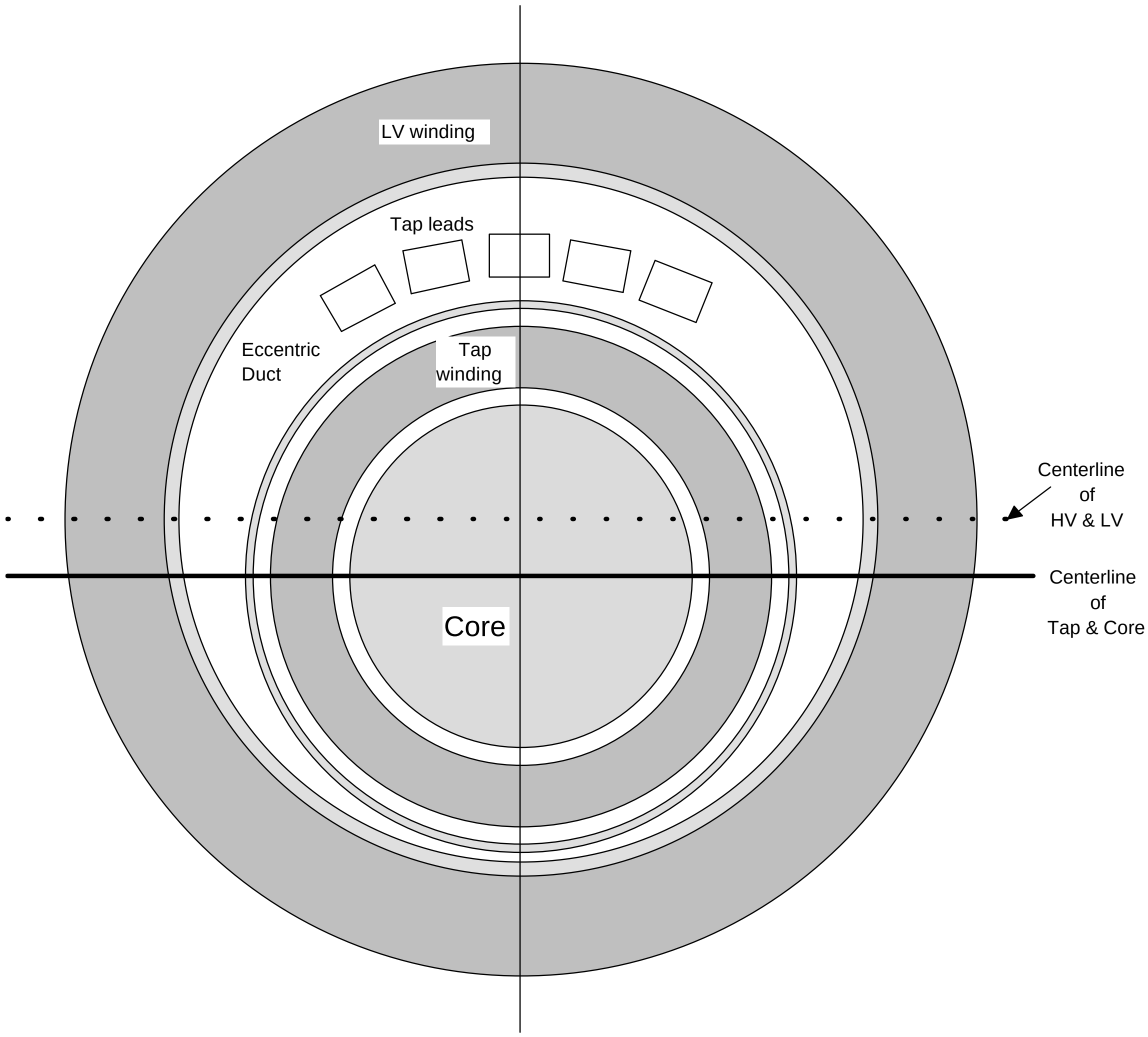


Figure 14: Eccentric Oil Duct for Tap Leads

OPERATION

If transformers are operated differently from the specification to which they are purchased, then there could be surprises. Almost all North American specifications specify the whole tap range for either constant flux or variable flux. Some specifications are not clear whether the taps are for constant flux or for variable flux. An example how it is stated in some specifications is ‘Taps are to be in the HV to keep the LV voltage constant’. It is not clear whether the taps in HV are to keep LV voltage constant for fluctuations in HV voltage or for the regulation on LV side. Transformers to such specifications are normally built with taps as constant flux taps because they are in general less costly than variable flux taps.

Impedance

Consider a core type step-down transformer with taps in HV for HV variation and the tap winding as the outer most winding. Such a transformer will have constant flux density in the core across the tap range and almost constant impedance across the tap range as long as volts per turn is kept constant i.e. HV taps are used to keep LV voltage constant for fluctuations in HV voltage.

Common practice in transformer stations is that a signal from the output (LV) controls operation of the tap changer to keep the output voltage constant. Consider a situation where the above transformer tries to compensate for regulation. When load on the transformer is increased, the output voltage drops and tap changer moves towards buck position (minimum HV turns position) to raise the output voltage. In such a situation volts per turn is increased as there is no change in input (HV) voltage and HV turns are reduced. Due to the increase in volts per turn, impedance will be reduced proportional to square of the volts per turn. A fault in this condition will result in higher short circuit currents leading to possible tripping of the circuit breaker or failure of the transformer and other equipment in the station. Operation of the transformer different from the specifications to which it was purchased may lead to warranty and legal problems.

Many users do not normally specify impedance at extreme tap positions in their specifications nor have asked for this information on the Data Sheets. If the impedance on an extreme tap position is low compared to that on the normal tap position then short circuit current on this extreme tap position could exceed the safe limit of the station. Circuit breaker capacity has to be checked for this higher short circuit current. If impedance on an extreme tap position is high compared to that on the normal tap position then regulation on this extreme tap position will be bad compared to that on the normal tap position.

Sound level

Almost all specifications specify sound level at rated tap only. A transformer purchased for constant flux operation but operated as a variable flux transformer will have different sound levels at different tap positions. At one extreme tap position sound level will be much higher than that at the normal tap and at the other extreme tap position sound level will be much lower. Consider a transformer purchased with taps in LV for LV variation and with LV as the output. When input voltage is increased, LV voltage is kept constant by adjusting the taps in LV but the sound level goes up due to increase in core flux density. In case of a variable flux design, an awareness of operation of the transformer at different tap positions and operating conditions is beneficial. It is advisable to know the sound level at rated tap position and also at extreme tap positions. With this information the transformer station can be designed to avoid potential environmental lawsuits.

Over excitation

Many users specify high over excitation (up to 1.38PU) requirement. This forces to design the transformer with low flux density resulting in considerable increase in transformer cost. It is understood that some of the reasons to specify such high over excitation are the way in which the motors of the tap changers are connected during parallel operation, runaway condition of tap changer motor etc. If users work with tap changer and transformer manufacturers then these problems can be avoided and no need to specify high over excitation requirement. When taps are on input side for input voltage variation (taps in HV for HV variation) then the effect of over excitation is for less compared to the effect when the taps are on the output side to compensate for regulation. Based on this, in many cases it is possible to reduce over excitation PU value and specification should take advantage of this situation.

Suggestion

If users obtain manufacturers' input at the time of writing the specification then operational, warranty and legal problems can be avoided.

GENERAL CONSIDERATIONS

1. **Gradient**: - Gradient is the difference between winding temperature and adjacent oil temperature. Electrically since taps are a part of the main winding, it is not possible to measure gradient of the tapping winding separately. Unless the tapping winding is brought out by test bushings to measure the gradient, it is preferable to design the tapping winding gradient to be same or lower than that of the main winding.

   Average gradients and hot spot temperatures of tapping winding and main winding should be calculated separately at maximum rating and also during overloads. When tapping winding and main winding rises are not measured separately then suggest that the calculated values are to be included on the test sheets. Based on physical location of the taps, special care is required to avoid problematic hot spots due to axial and radial leakage fluxes.

   Due to manufacturing difficulties, in directed oil flow transformers, oil is not usually pumped through the separate tapping winding. In such a case calculation of tapping winding average gradient and hot spot rise should be based on oil velocity in the tapping winding.

   If taps are brought out from an inner coil, especially when joints are made in the winding, then the tap leads should have proper cross-sectional area and cooling so that hot spot temperature will not exceed the standard limit.

2. **RCBN and FCBN**: - When system requirements permit it is recommended to specify RCBN (Reduced Capacity Below Normal) taps for economical reasons. With RCBN taps calculation of short circuit currents on tap positions below normal should be based on the rated MVA, only losses and gradient will be based on the reduced MVA.

   In considerable number of specifications with RCBN taps, overloads in MVA are specified but it is not stated that these overloads are applicable to the taps above normal only and only prorated overloads are applicable for the taps below normal.

   Cost savings between reversing taps and linear taps (or coarse/fine taps) is more substantial for FCBN (Full Capacity Below Normal) taps compared to the cost savings for RCBN taps.

3. **Tap changer rating**: - Some specifications state that current rating of tap changer should be higher than winding maximum current, such as 1.2 PU, 2 PU etc. In many cases with this requirement, needed current rating exceeds those of available tap changers and forces to use a series transformer adding additional cost and losses. Usual reason to specify these higher ratings for tap changers is to have more reliability but use of a series element (series transformer) will reduce overall reliability. It is advisable if users specify that LTC to meet C57.131 rather specifying higher than the required current ratings.

NON-LINEAR DEVICES TIE-IN RESISTORS AND TIE-IN CAPACITORS

Non-linear devices

Most commonly used non-linear devices are zinc oxide (ZnO) discs. Many transformers with ZnO discs across the tapping windings are in satisfactory operation for many years. ZnO discs reduce overall transformer cost and eliminate many design problems. When taps are at line end or in a location where high impulse voltage appears across the tapping winding, then use of ZnO discs is very useful. Compared to the non-linear devices that were available 30 years ago, present non-linear devices (ZnO discs) are very reliable and their characteristics almost do not change after many years in service. Due to a few bad incidents, some users state in their specifications that internal non-linear devices are not acceptable. If users check with transformer manufacturers how ZnO discs are mounted, test and operating voltages that appear across these discs etc, then these devices can be used to reduce costs and design problems.

Tie-in resistors and tie-in capacitors

During operation of changeover switch on reversing or coarse/fine LTC, the tapping winding is not connected to any point and will assume a potential based on capacitance coupling. Magnitude of this potential depends on physical location of the tapping winding, tap range and voltage across the main winding. Magnitude of this potential could exceed the safe value of the tap changer. To keep this voltage to a safe value, it is common practice to 'tie-down' the tapping winding with a resistor or a capacitor. Rating of tie-in resistor or tie-in capacitor is determined based on the capacitance between the tapping winding and the winding next to it and also from the tapping winding to ground.

Connection of tie-in resistors should be such that maximum losses in tie-in resistors appear on one or two tap positions only. For comparison it is recommended to measure no-load loss on these tap positions and record it on test report. When capacitors are used for tie-down then there will be no additional losses. To avoid problems in service, capacitance of the tie-down capacitors should be correctly chosen.

Suggestion

To produce reliable transformers economically, users should give freedom to manufacturers to use ZnO discs.

PREVENTIVE AUTOS AND SERIES TRANSFORMERS

Preventive autos: - In a reactor type tap changer, a preventive auto (tap changer reactor) bridges a tap and the bridging position is also a tap position. If only half the number of tap positions are needed, then the bridging positions can be ‘run through’ positions. Inductance of preventive auto to limit the circulating current during bridging position is very critical to the life of the tap changer. Tap changer manufacturer’s input is very important in designing the preventive auto. Based on tap changer model, suitability of the preventive auto design must be checked for normal operation and also for overloads. Common type of preventive auto uses gapped cores. Core packets design, length of air gaps etc. should be such that no problematic hot spots are developed during service life of the transformer. There had been cases where the clamping structures of the preventive autos were overheated. Since no separate temperature rise test is normally done on the preventive auto, users should be familiar with design and manufacturing practices of preventive autos. If the tap on which the losses are guaranteed is a non-bridging tap, then preventive auto losses are not included in the measurement. For temperature rise test, if the maximum loss tap position is not a bridging position then checking loss on a bridging tap position adjacent to the guaranteed tap position by test or by calculation is a good idea. It is also a good idea to do the temperature rise test on this bridging tap position if the losses are highest on this bridging tap position. Almost all of specifications specify that the sound level to be guaranteed on rated tap. If the rated tap is not a bridging position then preventive auto sound level is not included in the measurement.

Series transformer: - A series transformer provides more freedom in the design of the tap winding. But the series transformer will increase losses and cost of the transformer. Users should be aware that on neutral tap position, no-load loss of the series transformer is not included. In a transformer with reversing taps, the series transformer no-load loss is highest at both the extreme tap positions. Usually loss capitalization is done at rated tap only. Users should consider losses on other tap positions to evaluate overall life cycle costs. Overall reliability of the transformer with the series transformer should also be considered. In most cases no separate temperature rise test is done on the series transformer. If user is not satisfied with the design and the manufacturing practices of the series transformer, then it is beneficial to pay the manufacturer to include temperature measurements on the series transformer windings; these measurements can be done by providing temporary bushings on series transformer windings. Since transformer fault currents flow through series transformer it must be designed to withstand these currents.

Series transformers are primarily used to reduce current in tap changer or to obtain needed tap turns i.e. normally when taps are specified in LV winding. In some cases series transformers are used to reduce the step voltage also. Where possible by designing the series transformer as an autotransformer instead of a two winding transformer, cost and losses can be reduced. In certain designs placing taps in HV winding and eliminating the series transformer could be an economical option.

Suggestion: Based on operational needs and cost, users should allow manufacturers to decide whether to use a series transformer or to place the taps on HV winding.

CONCLUSIONS

1. Knowledge of how to determine type of taps, tap range, number of taps etc., to achieve least life cycle cost will be beneficial to users.

2. By tailoring the tap range and number of tap positions to suit the system needs, transformers with least life cycle cost can be purchased.

3. Familiarizing with design problems, design practices, ratings and types of tap changers available will result in writing better specifications.

4. It is safe not to assume that transformer designers know all system problems and system needs. Users should be aware that transformers will be designed only to meet what is stated in the specifications.

5. Specifications should not be based on a few bad incidents, obsolete materials, components and design practices. Specifications should reflect present improved materials and design practices.

6. Specifications should be functional ones rather based on a particular type of tap changer and/or taps.

7. (a) Users should give proper incentives to manufacturers to incorporate new developments in designs.

   (b) The biggest incentive users can give to transformer designers is to remove the sentence that “No prototype aspects will be considered” from their specifications. Most of the specifications specify to offer alternate bids but they are seldom considered.

8. Before specifying both DTC and LTC taps, users should consider to eliminate DTC taps. If required and if economical then LTC taps range can be increased to cover the DTC taps range.

9. Specifications should be clear as to whether taps are for constant flux or variable flux or mixed regulation (combined voltage regulation).

10. It will be educative and helpful if C57.12.00 includes a section on constant flux, variable flux and mixed regulation taps.

11. Clause 4.5 of C57.12.10 is to address the following.

    (i) Factors that will determine whether LTC should be on LV side or on HV side.
    (ii) Effects of impedance variation over the tap range on regulation, overloads and short circuit forces.

12. (a) For transformer ratings higher than 100 MVA many users are referencing C57.12.10 in their specifications, so also for HV voltage higher than 230KV and/or LV voltage higher than 36.23KV. As C57.12.10 reference transformer ratings up to 100MVA, HV 230KV and LV 36.23KV, it is preferable to limit this standard to the these ratings only.

    (c) To assist users to match their specifications with the standards, it will be helpful if IEEE issues an Addendum to C57.12.10 to cover transformer ratings above 100 MVA, HV voltage above 230KV and LV voltage above 36.23KV.

13. It will be mutually beneficial if users and manufacturers work together from the time specifications are being prepared.

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