

On-Load Tap-Changers for Power Transformers

A Technical Digest



On-Load Tap-Changers (OLTCs) are one of the indispensable components for the regulation of power transformers used in electrical energy networks and industrial application.

This paper explains the technological developments of resistor type OLTCs as well as of reactor type OLTCs. The general switching principles for OLTCs are discussed and applications of OLTCs are introduced.

Today's design concepts of OLTCs are described including the new generation of vacuum type OLTCs. The vacuum switching technology – used in OLTCs – is going to be the "state of the art" design at present time and foreseeable future. Examples of OLTC designs and the associated switching principles show the variety of the use of vacuum interrupters.

1. Introduction

Power transformers equipped with On-Load Tap-Changers (OLTCs) have been main components of electrical networks and industrial application for nearly 80 years. The OLTC allows voltage regulation and/or phase shifting by varying the transformer ratio under load without interruption.

From the beginning of Tap-Changer development, two switching principles have been used for the load transfer operation, the high-speed resistor type OLTC and the reactor type OLTC.

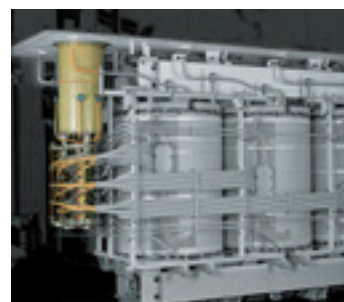
Over the decades both principles have been developed into reliable transformer components available in a broad range of current and voltage applications to cover the needs of today's network and industrial process transformers as well as ensuring an optimal system and process control [1].

The majority of resistor type OLTCs are installed inside the transformer tank (in-tank OLTCs) whereas the reactor type OLTCs are in a separate compartment which is normally welded to the transformer tank (Fig. 1).

The Paper mainly refers to OLTCs immersed in transformer mineral oil. The use of other insulating fluids or gas insulation requires the approval of the OLTCs manufacturer and may lead to a different OLTC design as shown in chapter 4.2.2.



compartment type



in-tank type

Fig. 1 OLTC arrangements

Switching Principle

2. Switching Principle

The OLTC changes the ratio of a transformer by adding turns to or subtracting turns from either the primary or the secondary winding. Therefore, the transformer is equipped with a so called regulating or tap winding which is connected to the OLTC.

Figure 2 shows the principle winding arrangement of a 3-phase regulating transformer, with the OLTC located at the wye-connection in the high voltage winding.

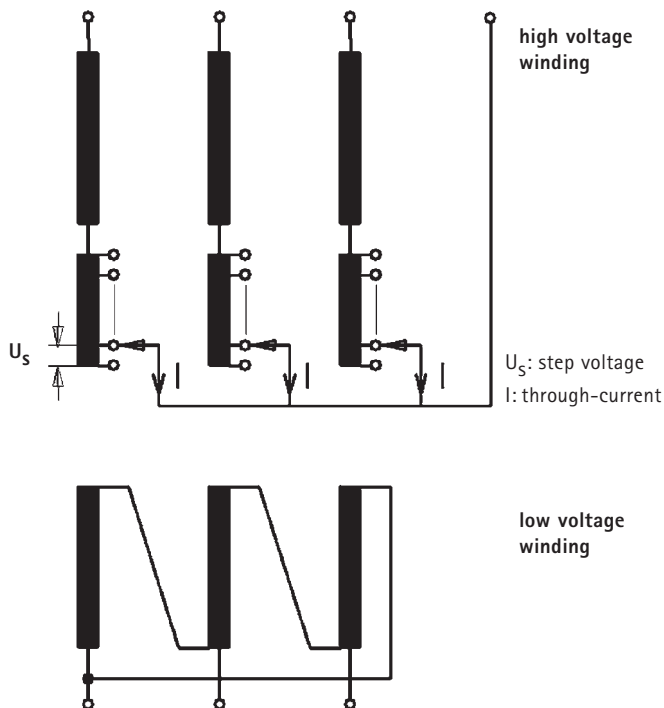


Fig. 2 Principle winding arrangement of a regulating transformer in wye-connection

Simple changing of taps during energized condition is unacceptable due to momentary loss of system load during the switching operation (Fig. 3). Therefore the "make (2) before break (1)" contact concept", shown in Figure 4, is the basic design for all OLTCs. The transition impedance in form of a resistor or reactor consists of one or more units that are bridging adjacent taps for the purpose of transferring load from one tap to the other without interruption or appreciable change in the load current. At the same time they are limiting the circulating current (I_c) for the period when both taps are used. Normally, reactor type OLTCs use the bridging position as a service position and, therefore, the reactor is designed for continuous loading.

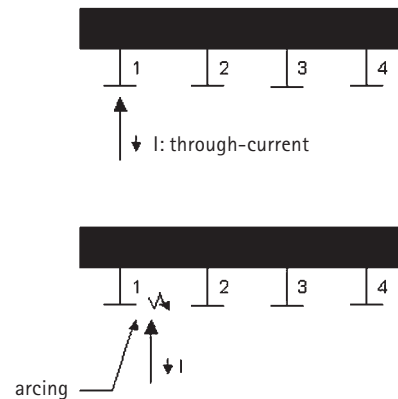


Fig. 3 Loss of system load with single contact switching

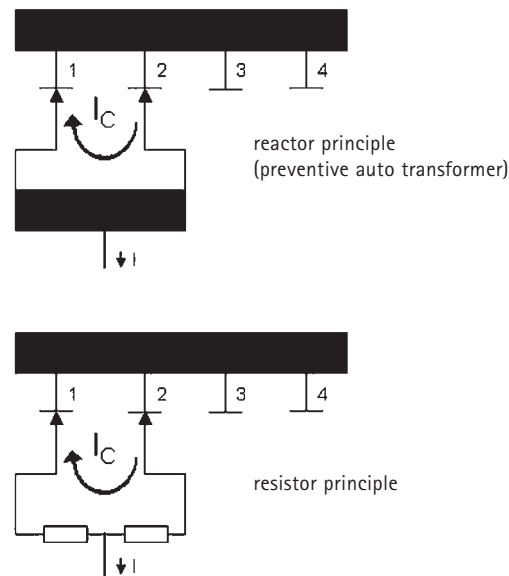


Fig. 4 Basic switching principle "make (2) before break (1)" using transition impedances

The voltage between the mentioned taps is the step voltage, it normally lies between 0.8 % and 2.5 % of the rated voltage of the transformer.

The main components of an OLTC are contact systems for make and break currents as well as carrying currents, transition impedances, gearings, spring energy accumulators and a drive mechanism. Depending on the various winding arrangements (details in chapter 3) and OLTC-designs, separate selector switches and change-over selectors (reversing or coarse type) are used in addition.

3. Applications of On-Load Tap-Changers

3.1 Basic Arrangements of Regulating Windings

The following basic arrangements of tap windings are used (Fig. 5):

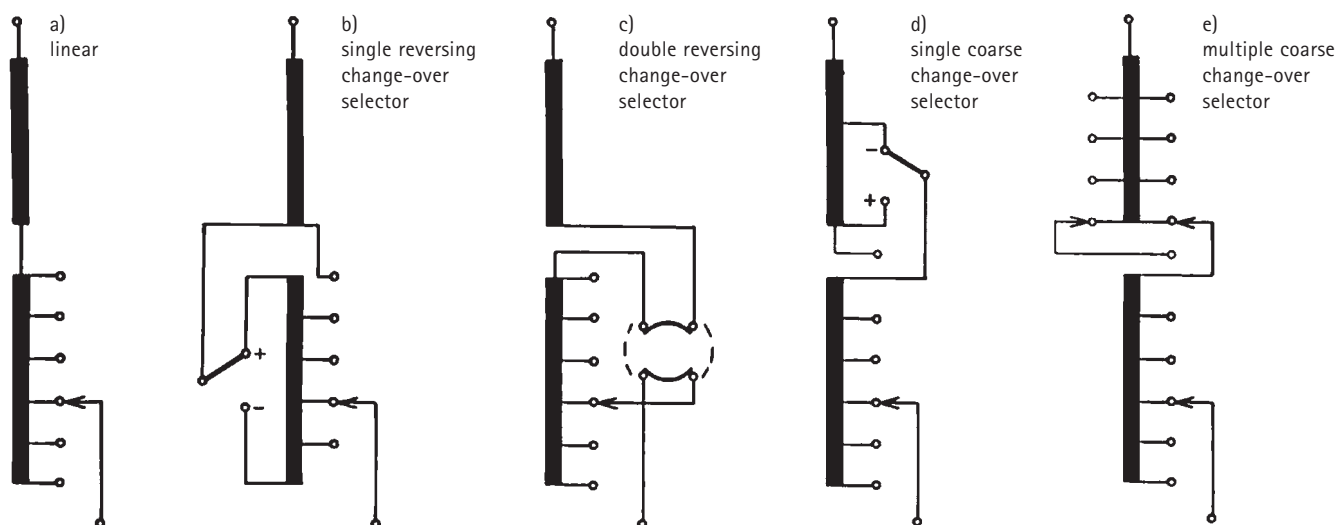


Fig. 5 Basic connections of tap windings

Linear arrangement (Fig. 5-a), is generally used on power transformers with moderate regulating ranges up to a maximum of 20%. The tapped turns are added in series with the main winding and changes the transformer ratio. The rated position can be any one of the tap positions.

With a reversing change-over selector (Fig. 5-b) the tap winding is added to or subtracted from the main winding so that the regulating range can be doubled or the number of taps be reduced. During this operation the tap winding is disconnected from the main winding (problems arising from this disconnection see chapter 6.2). The greatest copper losses occur, however, in the position with the minimum number of effective turns. This reversing operation is realized with the help of a change-over selector which is part of the tap selector or of the selector switch (arcing tap switch). The rated position is normally the mid one or neutral position.

The double reversing change-over selector (Fig. 5-c) avoids the disconnection of tap winding during the change-over operation. In phase-shifting transformers (PST) this apparatus is called advance-retard switch (ARS).

By means of a coarse change-over selector (Fig. 5-d) the tap winding is either connected to the plus or minus tapping of the coarse winding. Also during coarse selector operation the tap winding is disconnected from the main winding (special winding arrangements can cause same disconnection problems as above, in addition the series impedance of coarse winding/tap winding has to be checked see chapter 6.3). In this case the copper losses are lowest in the position of the lowest effective number of turns. This advantage, however, puts higher demands on insulation material and requires a larger number of windings.

The multiple coarse change-over selector (Fig. 5-e) allows a multiplication of the regulating range. It is mainly applied for industrial process transformers (rectifier/furnace transformers). The coarse change-over selector is also part of the OLTC.

It depends on the system and the operating requirements, which of these basic winding arrangements is used in the individual case. These arrangements are applicable to two winding transformers as well as to autotransformers and to phase-shifting transformers (PST). The location where the tap winding and therefore the OLTC is inserted in the windings (high voltage or low voltage side) depends on the transformer design and customer specifications.

3.2 Examples of Commonly Used Winding Schemes

Two winding transformers with wye connected windings have the regulation applied to the neutral end as shown in Figure 6. This results in relatively simple and compact solutions for OLTCs and tap windings.

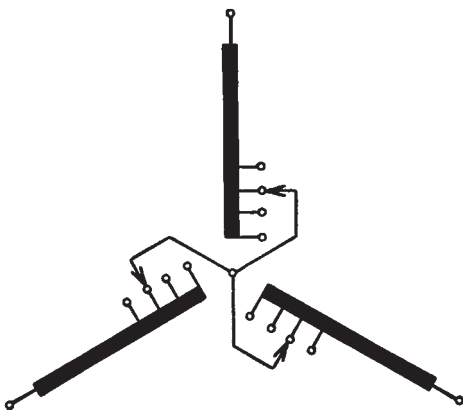
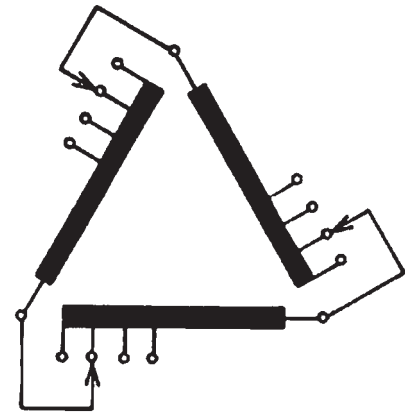
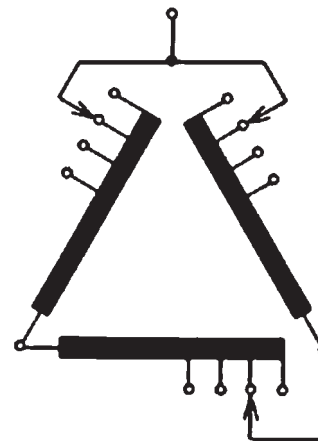


Fig. 6 OLTC with neutral end of tap winding

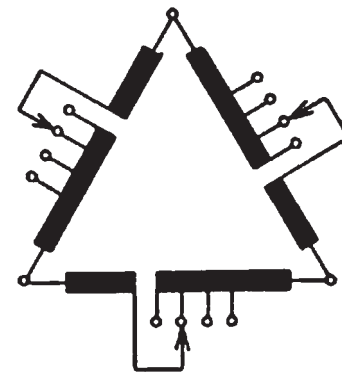
Regulation of delta connected windings (Fig. 7) requires a three-phase OLTC whose three phases are insulated according to the highest system voltage applied (Fig. 7-a), or 3 single-phase OLTCs, or 1 single-phase and 1 two-phase OLTC (Fig. 7-b). Today, the design limit for three-phase OLTCs with phase-to-phase insulation is the highest voltage for equipment of 145 kV (BIL 650 kV). To reduce the phase-to-phase stresses on the delta-OLTC the three pole mid-winding arrangement (Fig. 7-c) can be used.



a) three pole line-end arrangement



b) one and two pole line-end arrangement



c) three pole mid-winding arrangement

Fig. 7 OLTC with delta-connection of tap winding

For regulated autotransformers, Fig. 8 shows various circuits. In dependence on their regulating range, system conditions and/or requirements, weight and size restrictions during transportation, the most appropriate scheme is chosen. Autotransformers are always wye-connected.

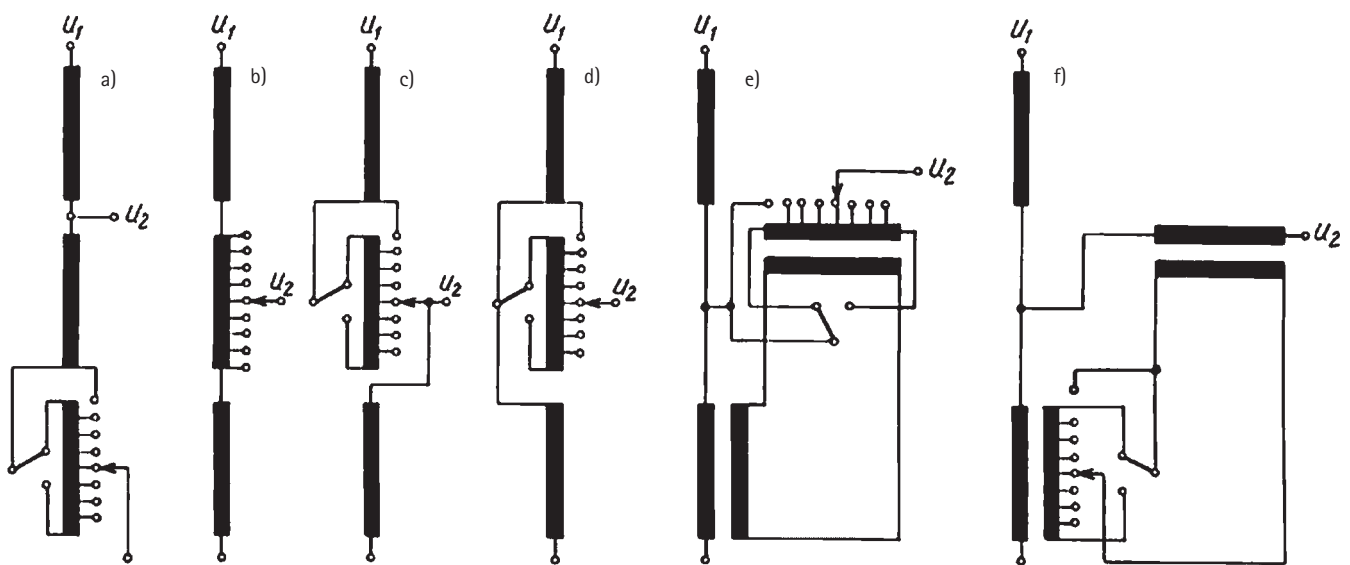


Fig. 8 OLTCs in autotransformers

- Neutral end regulation (Fig. 8-a) may be applied with a ratio above 1 : 2 and a moderate regulating range up to 15%. It operates with variable flux.
- A scheme shown in Fig. 8-c is used for regulation of high voltage U_1 .
- For regulation of low voltage U_2 the circuits Fig. 8-b, 8-d, 8-e and 8-f are applicable. The arrangements Fig. 8-e and 8-f are two core solutions. Circuit Fig. 8-f is operating with variable flux in the series transformer, but it has the advantage that a neutral end OLTC can be used. In case of arrangement according to Fig. 8-e main and regulating transformer are often placed in separate tanks to reduce transport weight. At the same time this solution allows some degree of phase shifting by changing the excitation-connections within the intermediate circuit.

3.3 Phase-Shifting Transformers (PST)

In the last years the importance of phase-shifting transformers used to control the power flow on transmission lines in meshed networks has steadily been increasing [2].

The fact that IEEE provides a "Guide for the Application, Specification and Testing of Phase-Shifting Transformers" [3] proves the demand for PSTs.

These transformers often require regulating ranges which exceed those normally used. To reach such regulating ranges, special circuit arrangements are necessary. Two examples are given in Fig. 9 and Fig. 10. Fig. 9 shows a circuit with direct line-end regulation, Fig. 10 an intermediate circuit arrangement. Fig. 9 illustrates very clearly how the phase-angle between the voltages of the source- and load-system can be varied by the LTC position. Various other circuit arrangements have been realized.

The number of LTC operations of PSTs is much higher than that of other regulating transformers in networks (10 to 15 times higher). In some cases, according to regulating ranges – especially for line-end arrangements (Fig. 9) – the transient overvoltage stresses over tapping ranges have to be limited by the application of non-linear resistors. Furthermore the short-circuit current ability of the OLTC must be checked, as the short-circuit power of the network determines the said current. The remaining features of LTCs for such transformers can be selected according to usual rules (see chapter 6).

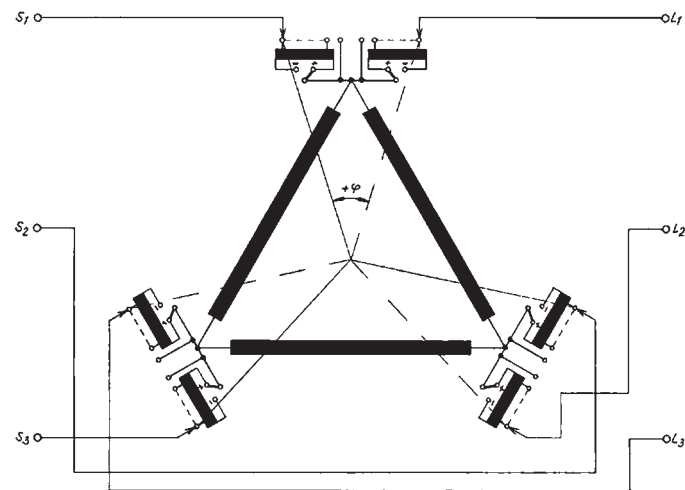


Fig. 9 Phase-Shifting Transformer – direct circuit arrangement

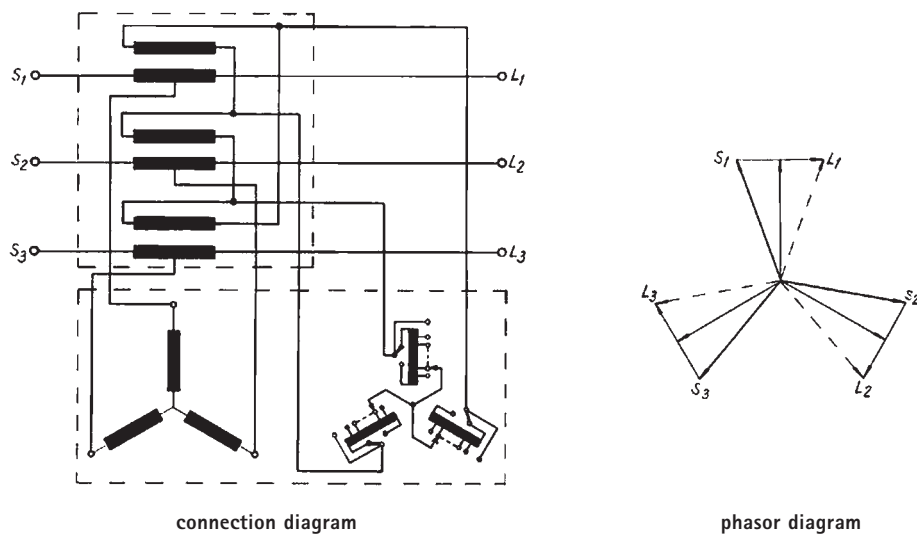


Fig. 10 Phase-Shifting Transformer – intermediate circuit arrangement

Significant benefits resulting from the use of a PST are:

- Reduction of overall system losses by elimination of circulating currents
- Improvement of circuit capability by proper load management
- Improvement of circuit power factor
- Control of power flow to meet contractual requirements

4. Design Concepts of Today's On-Load Tap-Changers

Beside the selection of taps, the most important duty of an OLTC is the break function or current (load) transferring action (see Fig. 4). After transferring the current, the contact which "breaks" must be capable to withstand the recovery voltage. The so called required switching capacity (product of switched current and recovery voltage) for a specific contact in an OLTC is based on the relevant step voltage and current but is also determined by the design and circuit of the OLTC. The switching capacity itself is primarily a function of the contact design, contact speed and arc quenching agent.

Since historical most power transformers use mineral oil as a cooling and insulation medium. Also the development of OLTCs toward the present "state of the art" designs was focused on transformer oil. Beside the insulation properties of the transformer oil, the arc quenching behavior for the switching contacts determined the design and size of so called "oil type" OLTCs.

Oil type OLTC means the OLTC is immersed in transformer oil and switching contacts makes and breaks current under oil (examples see chapter 4.1). This conventional OLTC technology has reached a very high level and is capable of meeting most requirements of the transformer manufacturer. This applies to the complete voltage and power fields of today, which will probably remain unchanged in the foreseeable future.

Along with the increase in demand for electrical energy in metropolitan areas, the necessity for installing transformers in buildings creates a need for regulating transformers with reduced fire hazards. In addition to this and with respect to the prevention of water pollution, those regulating transformers are preferable that do not require conventional mineral oil as insulating or switching medium.

Apart from gas-immersed transformers, mainly used in Japan, dry-type transformers, and transformers with alternative insulating fluids meet these requirements, which are increasingly asked for.

For these kind of regulating transformers, the conventional tap-changers are little suitable, because the use of mineral oil as switching medium is – for the reasons mentioned above – not desirable and would moreover require technically complex and expensive overall solutions.

Furthermore worldwide deregulation in the electric industry is still of concern. As part of this market, mechanisms have been encouraged to price transmission services and encourage both generation and transmission investment. In consequence, increased cost pressure on utilities as well as for the industry has led to increased performance expectations on the transformer equipment and OLTC, in particular

- Long-term uninterrupted availability of the regulating transformer, i. e.
 - > extension of the maintenance intervals
 - > reduction of the maintenance work
- Low failure rate
- Reduction of the operating costs

For all above mentioned new application fields and increased performance expectations a new common switching technology was asked for.

Various approaches with solid state technology are being discussed since the eighties, like Static OLTCs and Hybrid OLTCs as resistor or commutating type, but only a few applications have been realized.

More successful was the first use of vacuum interrupters in reactor type OLTCs in the USA which started at the same time. The size of the vacuum interrupters at that time, especially for the range of high currents, was not a limiting factor because of the compartment type design but not so for in tank resistor type OLTCs.

Looking at the overall profile of

- Quality
- Reliability
- Economy
- OLTC lifespan
- Range of ratings

at present time and foreseeable future the Vacuum Switching Technology in OLTCs provides the best solution for today's expectations.

All new OLTC designs (resistor and reactor type) of Maschinenfabrik Reinhausen GmbH are based on the Vacuum Switching Technology. Therefore these new designs are described in more details (see chapter 4.2) compared to oil type OLTCs.

4.1 Oil Type OLTCs – OILTAP®

4.1.1 Resistor Oil Type OLTCs

The OLTC design that is normally applied to larger powers and higher voltages, comprises a diverter switch (arcing switch) and a tap selector. For lower ratings OLTC designs are used, where the functions of the diverter switch (arcing switch) and the tap selector are combined in a so-called selector switch (arcing tap switch).

With an OLTC comprising a diverter switch (arcing switch) and a tap selector (Fig. 11), the tap change operation takes place in two steps (Fig. 12). First the next tap is preselected by the tap selector at no load (Fig. 12 position a-c). Then the diverter switch transfers the load current from the tap in operation to the preselected tap (Fig. 12 position c-g). The OLTC is operated by means of a drive mechanism. The tap selector is operated by a gearing directly from the drive mechanism. At the same time, a spring energy accumulator is tensioned, this operates the diverter switch – after releasing in a very short time – independently of the motion of the drive mechanism. The gearing ensures that this diverter switch operation always takes place after the tap preselection operation has been finished. The switching time of a diverter switch lies between 40 and 60 ms with today's designs. During the diverter switch operation, transition resistors are inserted (Fig. 12 position d-f) which are loaded for 20–30 ms, i. e. the resistors can be designed for short-term loading. The amount of resistor material required is therefore relatively small. The total operation time of an OLTC is between 3 and 10 sec depending on the respective design.

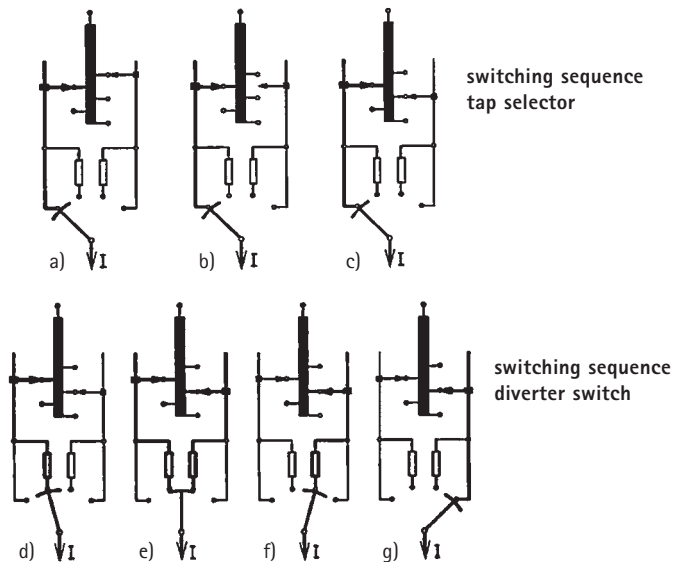


Fig. 12 Switching sequence of tap selector – diverter switch (arcing switch)

A selector switch (arcing tap switch) as shown in Fig. 13 carries out the tap change in one step from the tap in service to the adjacent tap (Fig. 14). The spring energy accumulator, wound up by the drive mechanism actuates the selector switch sharply after releasing. For switching time and resistor loading (Fig. 14 position b-d), the above statements are valid. The details of switching duty including phasor diagrams are described in annex A of [4], [5] and [6].

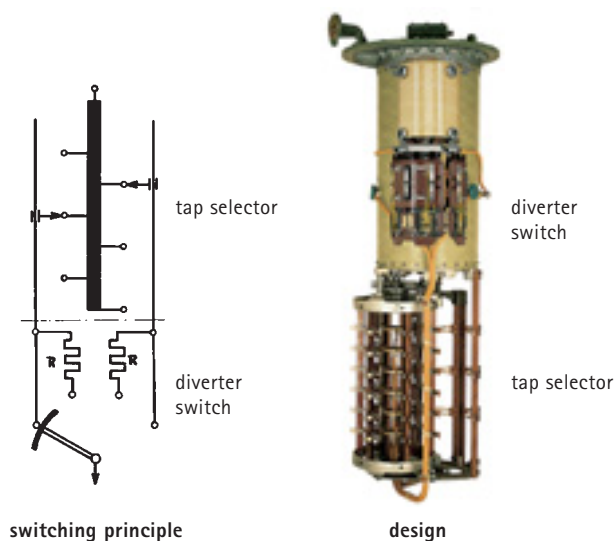


Fig. 11 Design principle – diverter switch (arcing switch) with tap selector
OILTAP® M

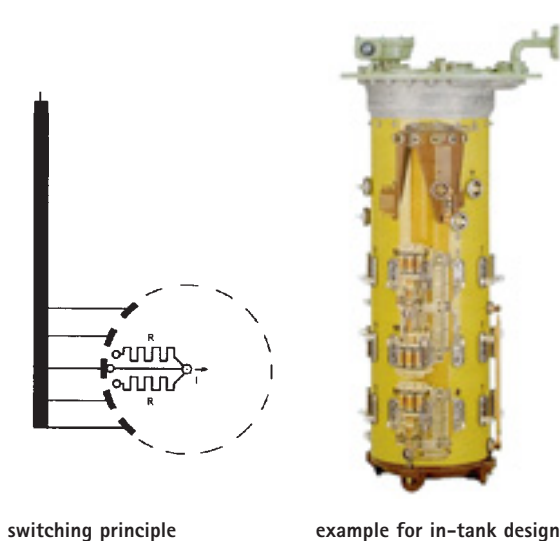


Fig. 13 Design principle – selector switch (arcing tap switch)
OILTAP® V

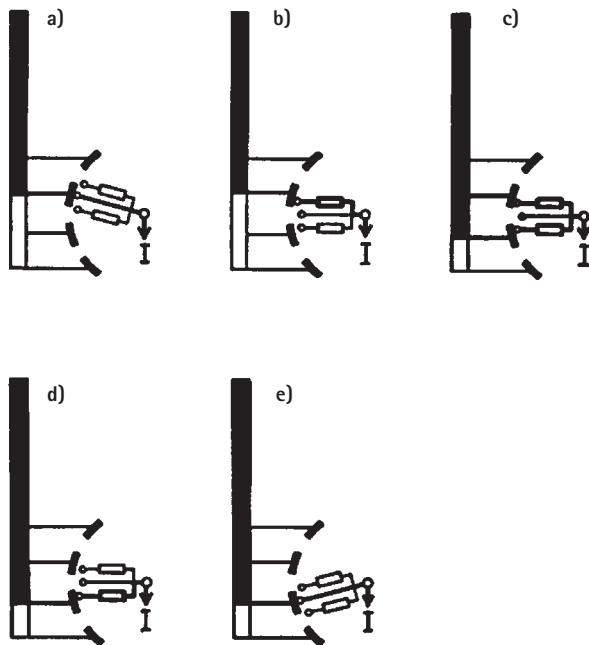


Fig. 14 Switching sequence of selector switch (arcing tap switch)
OILTAP® V

4.1.2 Reactor Oil Type OLTCs

For reactor oil type OLTCs the following types of switching are used:

- Selector switch (arcing tap switch)
- Diverter switch (arcing switch) with tap selector

All reactor type OLTCs are compartment types where the preventive autotransformer (reactor) is not part of the OLTC. The preventive autotransformer is designed by the transformer manufacturer and located in the transformer tank.

Today only selector switches (arcing tap switches) for voltage regulators are still in production whereas the reactor vacuum type OLTCs (see chapter 4.2.2 and 4.2.4.3) are going to be the state of the art in the field of power transformers. Therefore this oil technology is not further discussed in this paper. For more detailed information about switching duty and phasor diagrams of reactor oil type OLTCs see annex B of [4] and [6].

4.2 Vacuum Type OLTCs – VACUTAP®

4.2.1 Fundamentals of Vacuum Switching Technology

In the course of the last two decades the vacuum switching technology has become the predominant switching technology in the areas of medium voltage substations and high capacity power contactors and has replaced oil- and SF₆-technology. Today worldwide more than 60% of the demand for circuit breakers in the medium power voltage segment is covered by vacuum type circuit breakers [7], [8], [9].

The vacuum switching technology offers also the best qualification to meet new application requirements and increased performance demands from endusers on OLTCs. Its superiority to competing switching technologies in the range of low and medium power is based on a number of its technical features [10], [11]:

- The vacuum interrupter is a hermetically sealed system
 - There is no interaction with the surrounding medium, despite the arc
 - The switching characteristics do not depend on the surrounding medium
- The arc (drop) voltage in vacuum is considerably lower than in oil or SF₆
 - Low energy consumption
 - Reduced contact wear
- Elimination of the insulating medium as the arc quenching agent
 - Elimination of by-products e.g. carbon when using transformer oil
 - On-line filter becomes unnecessary
 - Easy disposal
- No ageing of the quenching medium
 - Constant or even improving switching characteristics throughout the entire life of the vacuum interrupters (getter effect)
- No interaction/oxidation during switching
 - High rate of recondensation of metal vapor on contacts extends contact life
 - Constantly low contact resistance
- Extraordinary fast dielectric recovery of up to 10 kV/μs
 - Ensures short arcing times (maximum one half-cycle) even in case of large phase angles between current and voltage or high voltage steepness dU/dt after the current zero (converter transformers).

Design Concepts of Today's On-Load Tap-Changers

4.2.2 Application of the Vacuum Switching Technology to On-Load Tap-Changers

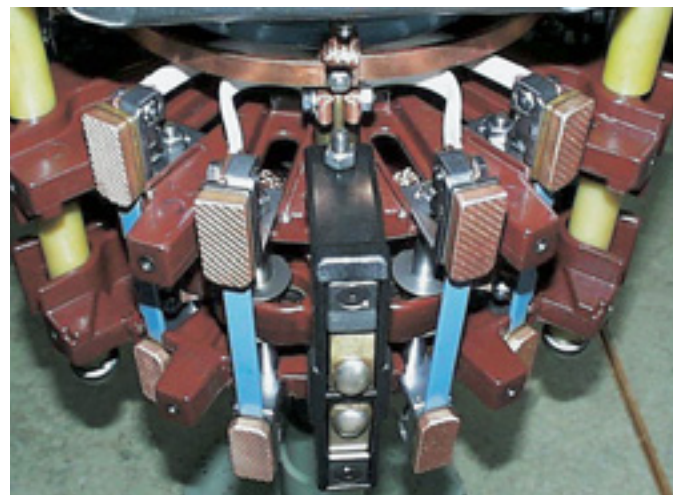
When developing a vacuum interrupter for use in an OLTC, the unique parameters are:

- Mechanical life in transformer oil (or any other given insulating medium) for the operating temperature range and expected life time of the OLTC
- Switching performance
- Contact life
- Physical dimension

Since the early seventies vacuum interrupters that fulfilled the characteristics required by reactor type OLTCs have been developed. These OLTCs, which in general are external compartment type designs, did not dictate any special requirements in regards to the physical size of the interrupter. Not so with resistor type OLTCs, which in general have a very compact design. Today, after more than three decades of development, vacuum interrupters have reached an advanced technical performance level. The use of modern clean room and furnace soldering technologies during the production process, and new designs of contact systems and material are some of the milestones for this reliable product. This has made possible the design of considerably smaller vacuum interrupters, opening the door for its application in resistor type OLTCs with overall dimensions equivalent to those of conventional resistor type OLTC designs (see Fig. 15 and 16).



selector switch contact system with roller contacts



diverter switch contact system

Fig. 15 OLTCs with tungsten-copper arcing contact system for mineral transformer oil (different scales)



Fig. 16 Vacuum interrupter designed for different OLTC diverter switches

Design Concepts of Today's On-Load Tap-Changers

Reinhausen started producing vacuum reactor type OLTCs in the mid-eighties. Since the introduction in 1990 of a new designed reactor type OLTC using vacuum interrupters (Fig. 17), more than 5,000 units have been produced. This number represents a total of 15,000 vacuum interrupters in service. Particularly in industrial applications (furnace transformers) with extremely high number of switching operations (>100,000 per year) vacuum interrupters have demonstrated their safe operation and superiority compared to the conventional switching process in oil.

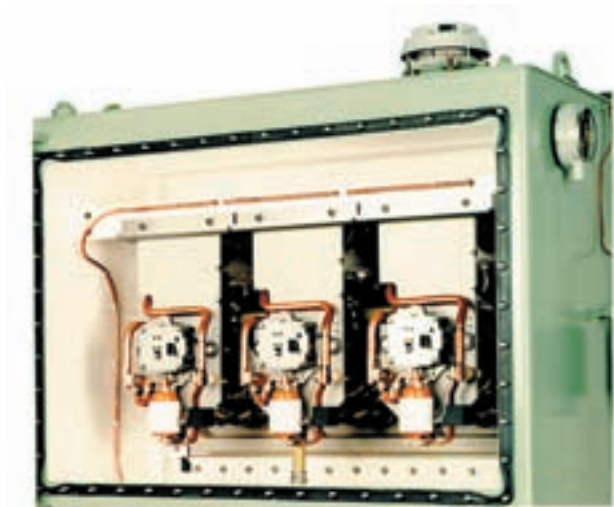


Fig. 17 Reactor vacuum type OLTC with one vacuum interrupter per phase – VACUTAP® RMV

Some units have already reached the remarkable number of 1,000,000 operations under load condition where the vacuum interrupters have been changed the first time as a precaution measure. As mentioned before, this is due to the extreme low loss of contact material of vacuum interrupters.

In Figure 18 the contact wear due to current breaking is shown for conventional copper-tungsten contacts under oil and for vacuum interrupters. The rate is more than one decade smaller for vacuum interrupters (e.g. rate: 1/30 at 1,000 A). Beside the contact material the contact geometry is the most important factor for this current range and OLTC applications. This results in contact life, where vacuum interrupters easily reach numbers of switching operations over 500,000 without changing the interrupters.

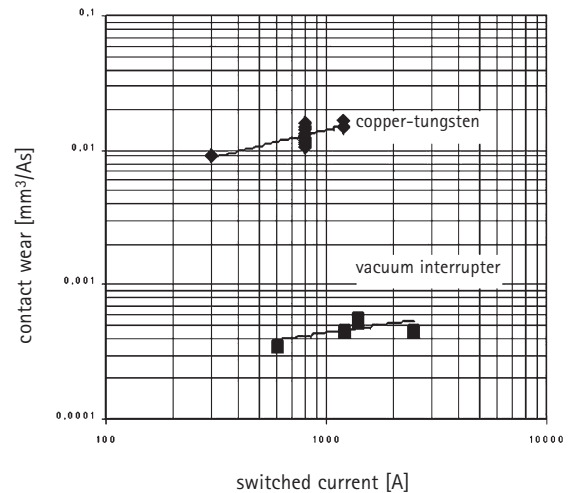


Fig. 18 Comparison of the rates of contact wear of conventional copper-tungsten contacts and vacuum interrupters

In parallel to the above mentioned development in the field of reactor type tap-changers, in 1995 the first resistor type OLTC using vacuum interrupters was designed for the regulation of dry-type transformers and therefore operates in air (see Fig. 19). So far close to 600 single-phase units with 1,800 vacuum interrupters have been built and are in service successfully.

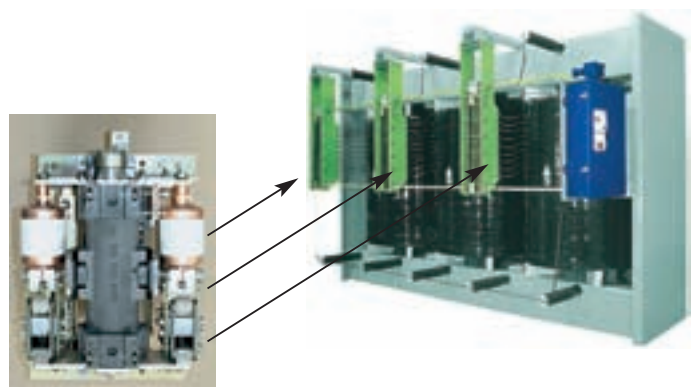


Fig. 19 Resistor vacuum type OLTC for dry-type transformers VACUTAP® VT

Design Concepts of Today's On-Load Tap-Changers

Since the year 2000 there is the first commercially available high-speed resistor vacuum type OLTC for in-tank installations (see Fig. 21). It represents the first step of the implementation of the vacuum switching technology in the worldwide-applied in-tank OLTCs for oil filled power transformers.

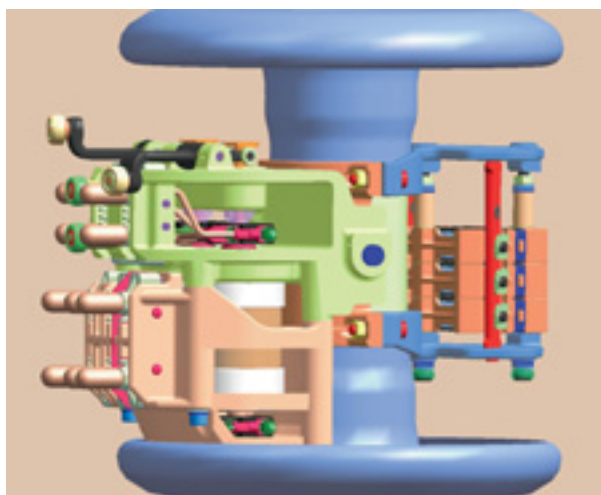


Fig. 20 Resistor vacuum type OLTC for in-tank installations in oil filled power transformers – VACUTAP® VV

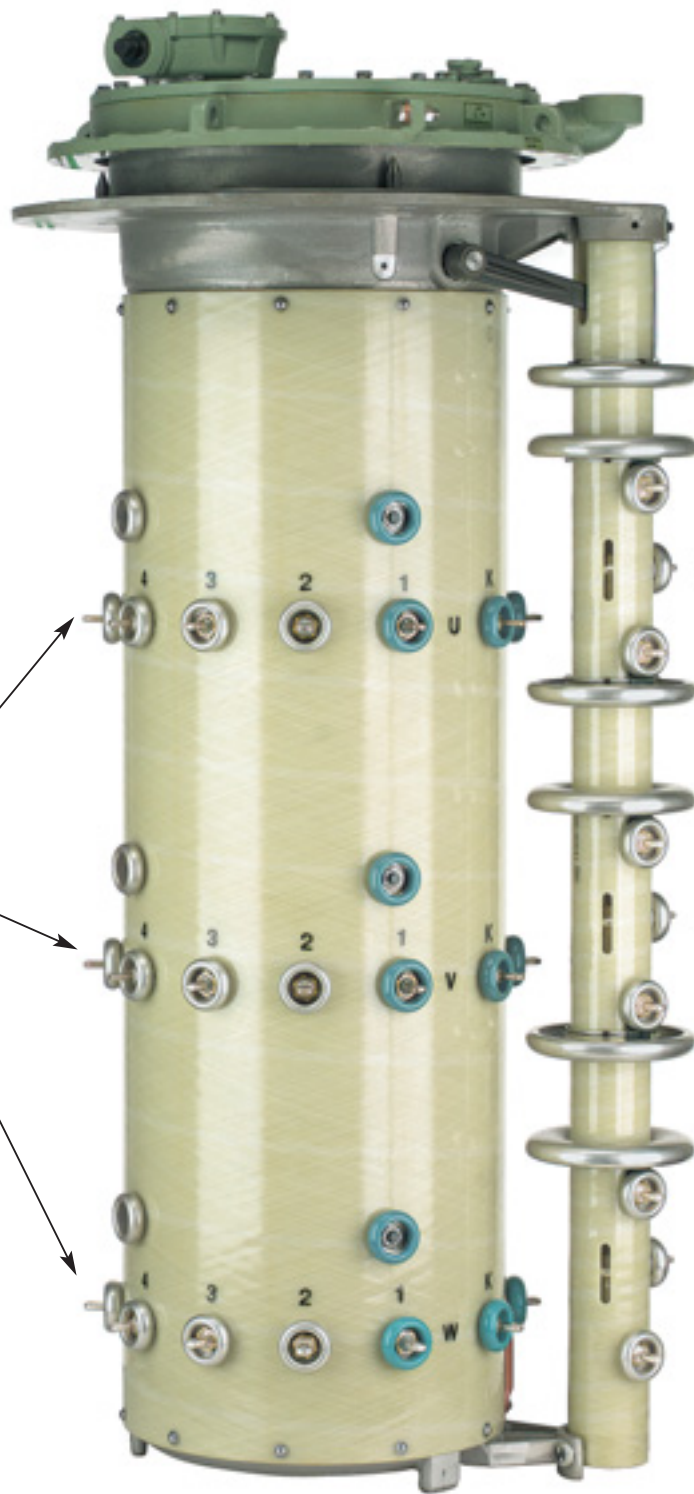


Fig. 21 VACUTAP® VV



Fig. 22 VACUTAP® VR

4.2.3. VACUTAP® VR

The VACUTAP® VRC/VRE 700 have made a name for themselves around the world. Starting in 2006, we are expanding the high end of the performance spectrum with the new VACUTAP® VR 1300 (Fig. 22).

The result: significantly reduced operating costs combined with maximum quality and highest environmental and safety standards.

Advantages VACUTAP® VR:

- Experience with the state-of-the-art vacuum switching technology since the 80ies, i.e. 8,000 VACUTAP® OLTCs are in use worldwide.
- Maintenance-free for up to 300,000 operations
 - No time based maintenance
 - Maintenance-free for almost all network applications
 - Significant reduction of life-cycle-costs
 - Increased transformer availability
- Friendly to the environment
 - No oil carbonization: no arcing in the insulating oil
 - No oil filter unit
 - Extended lifespan of the insulating oil
- Designed for selected, alternative liquids
- Extended application of VACUTAP® VR for autotransformers, for regulation at beginning of the delta winding, for HVDC transformers and for sealed transformers
- Ideal for industrial applications and for application in potentially explosive areas
- Vacuum switching technology now also available for almost all the extensive OILTAP® R/RM and M program
- Same diameter (740 mm) of the on-load tap-changer head, same diameter (478 mm) of the oil compartment as for OILTAP® R/RM and M – only minor changes in installation length

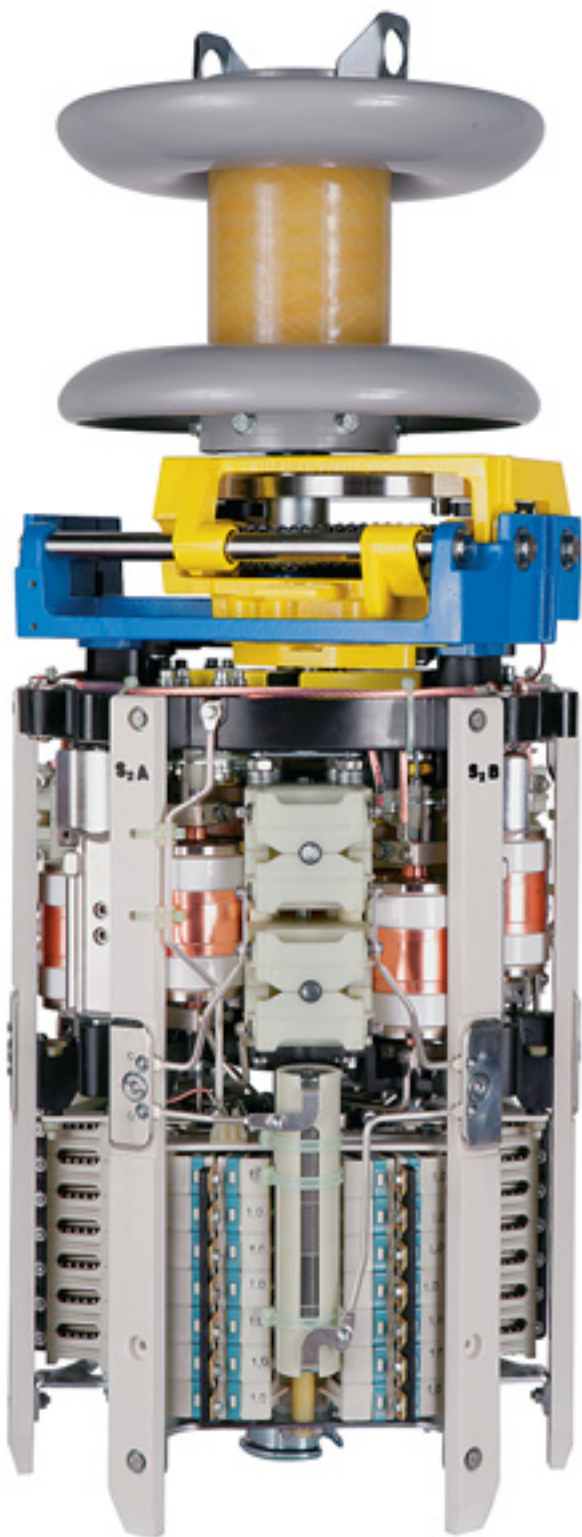


Fig. 23 Diverter switch insert of VACUTAP® VR

4.2.4 The Switching Principles of Resistor and Reactor Vacuum Type OLTCs

The switching principles of vacuum type OLTCs differ from those of conventional ones. A simple duplication of the switching contacts of a conventional OLTC with vacuum interrupters would lead to a solution which is unnecessarily more expensive and greater in volume. Therefore, special designs with special switching principles were created on the one hand to reduce the number of necessary vacuum interrupters, but on the other hand to increase the switching duty only a little bit. In the following, two possible designs are introduced.

4.2.4.1 Switching Principle of a Resistor Vacuum Type OLTC – VACUTAP® VV

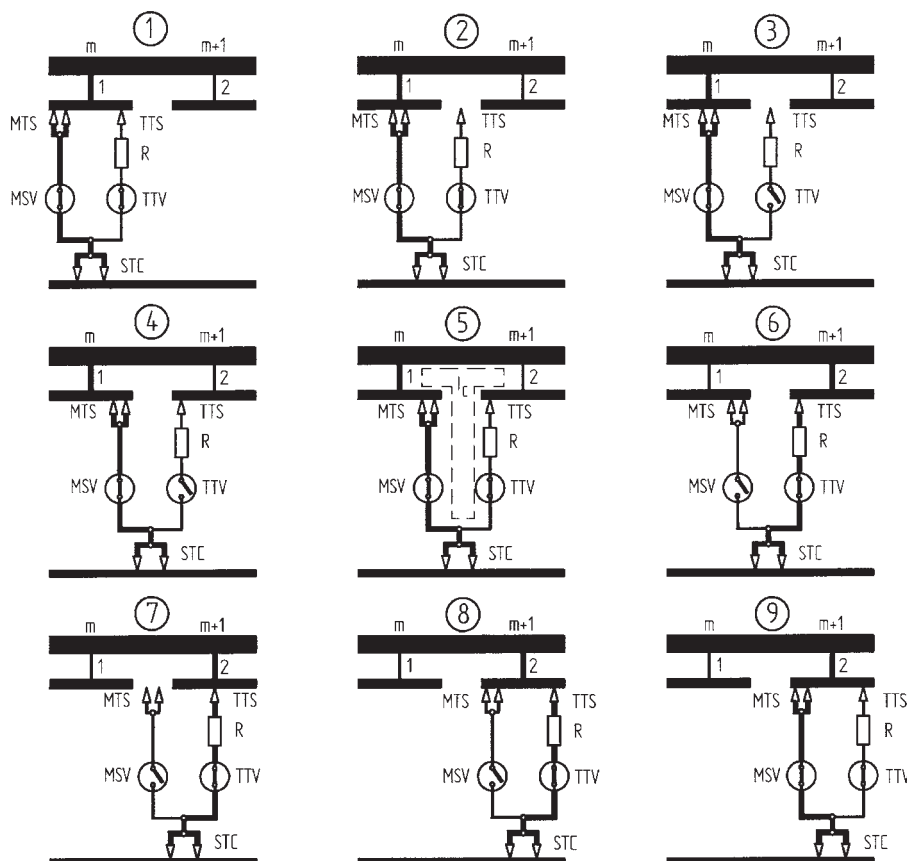
Usually, a conventional resistor type OLTC has different sets of switching contacts for the opening and the closing side of the diverter switch. One idea to reduce the number of vacuum interrupters needed is to use the same vacuum interrupters for the opening and the closing sides. This method was applied for the switching principle shown below (Fig. 24) and is used in the resistor vacuum type OLTC in Figure 20.

This tap changer incorporates two current paths. The main path comprises the main switching contacts (vacuum interrupter MSV) and the corresponding main tap selector contacts MTS connected in series. The transition path comprises the transition contacts (vacuum interrupter TTV) with the corresponding transition tap selector contacts TTS connected in series, and the transition resistor R. The sequence of operation is shown in Figure 24. In the initial position (step 1) at tap 1 both vacuum interrupters are closed. Consequently the interrupters are not exposed to a voltage stress. The tap change operation starts with the opening of the transition

tap selector contacts TTS (step 2). The vacuum interrupter TTV in the transition path opens (step 3) before the transition tap selector contacts TTS close on the adjacent tap eliminating the possibility of a pre-discharge arc. Once the transition tap selector contact TTS has reached the adjacent tap (step 4), the vacuum interrupter TTV closes (step 5) and a circulating current starts to flow.

The circulating current is driven by the voltage difference between the two adjacent taps and is limited by the transition resistor R. Subsequently, the vacuum interrupter MSV opens (step 6) transferring the current flow from the main tap selector contacts MTS to the transition path. The load current now flows through tap 2. The main tap selector contacts can now move load free to the adjacent tap (steps 7 and 8). The tap change operation is finalized with the closing of the vacuum interrupter MSV, which shunts the transition path (step 9).

Tap change operations in this direction ($m \rightarrow m+1$), here defined as "raise", follow the described sequence of steps 1 through 9. On the other hand, tap change operations in the "lower" direction follow the inverse order of events (steps 9 through 1).



MTS	Tap selector contacts, main path
MSV	Main switching contacts (vacuum interrupter), main path
TTS	Tap selector contacts, transition path
TTV	Transition contacts (vacuum interrupter), transition path
STC	Sliding take-off contacts
R	Transition resistor
I_c	Circulating current
$m, m+1$	Tap m , tap $m+1$

Fig. 24 Switching sequence of resistor type OLTC with the same vacuum interrupters for the closing and opening side of the diverter switch – VACUTAP® VV

4.2.4.2 Switching Principle of a Resistor Vacuum Type OLTC – VACUTAP® VR

The basic VACUTAP® VR features (number of vacuum interrupters required and current paths, i.e. one main path and one transition path) match those of VACUTAP® VV (section 4.2.4.1).

In the VACUTAP® VR model, the continuous current carrying capabilities of MSV and MTF, which are connected in series, are exceeded due to higher rated through currents. These switches therefore require a shunt circuit at the basic positions (side A and B), which are connected and disconnected by the main contacts (MCA) and (MCB).

The sequence of operation is shown in Fig. 25. Initially, both vacuum interrupters are closed (step 1). Consequently, the interrupters are neither exposed to a voltage stress nor a load current.

The tap change operation starts with opening of MCA, which commutates the load current from the continuous current path to the main path, causing it to flow through MSV and MTF (step 2).

The vacuum interrupter MSV then opens (step 3) and transfers the load current from the main path to the transition path, where it flows through TTF, TTV, and the transition resistor R.

Now MTF turns (without current) from side A to side B (step 4) connecting MSV (still in off-state) from side A to side B.

MSV then closes again (step 5) and a circulating current starts to flow. Both MSV and MTF are subjected to the sum of the load current and the circulating current.

TTV then opens (step 6), interrupting the circulating current.

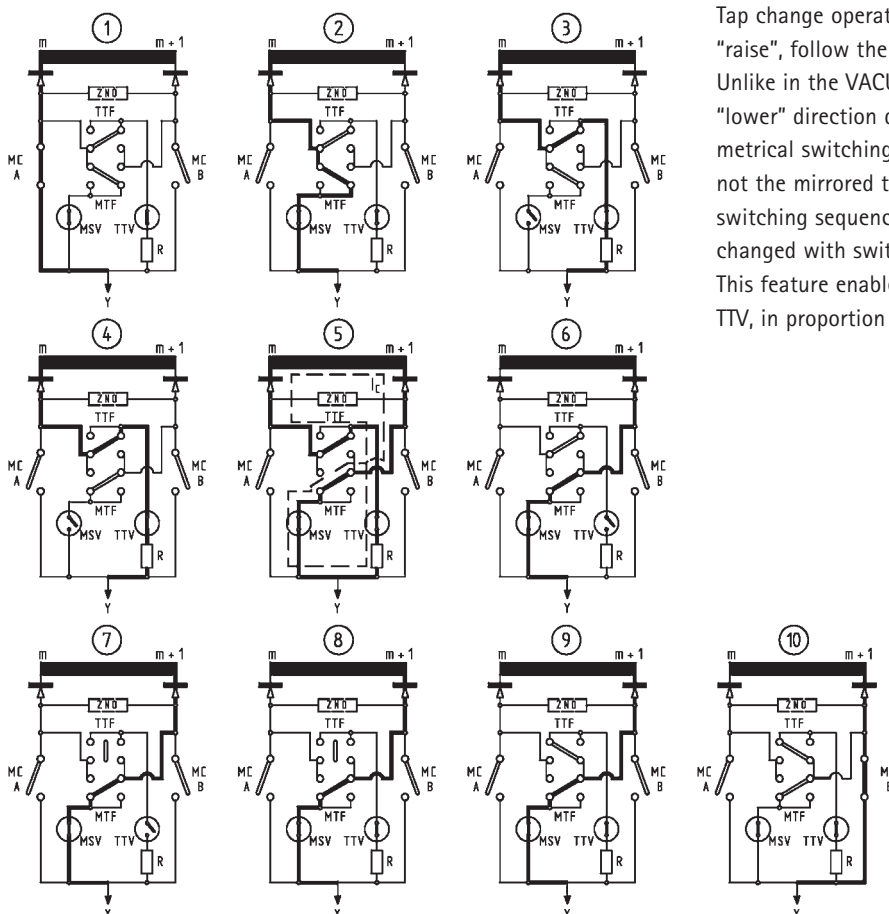
TTF now starts turning from side A to side B (step 7), while TTV closes again (step 8).

TTF is connected to side B once TTV has closed (step 9). However, TTF is not about to switch on current, because side B is already shunted by the main path MSV/MTF.

The final tap change operation step is closing of MCB (step 10), which transfers the load current to the continuous current path.

Tap change operations in this direction ($m \rightarrow m+1$), here defined as "raise", follow the sequence described in step 1 through 10.

Unlike in the VACUTAP® VV model, tap change operations in the "lower" direction do **not** follow the reverse order, due to an asymmetrical switching sequence. Tap change operation from B \rightarrow A is not the mirrored tap change operation A \rightarrow B. To illustrate the switching sequence B \rightarrow A the labelling A and B has to be interchanged with switching steps 1 through 10 remaining unchanged. This feature enables optimization of switching stresses on MSV and TTV, in proportion to the step capacity.



- MSV** Main switching contacts (vacuum interrupter), main path
- MTF** Transfer switch, main path
- TTV** Transition contacts (vacuum interrupter), transition path
- TTF** Transfer switch, transition path
- MCA** Main contacts side A
- MCB** Main contacts side B
- ZNO** ZNO-arrester
- R** Transition resistor

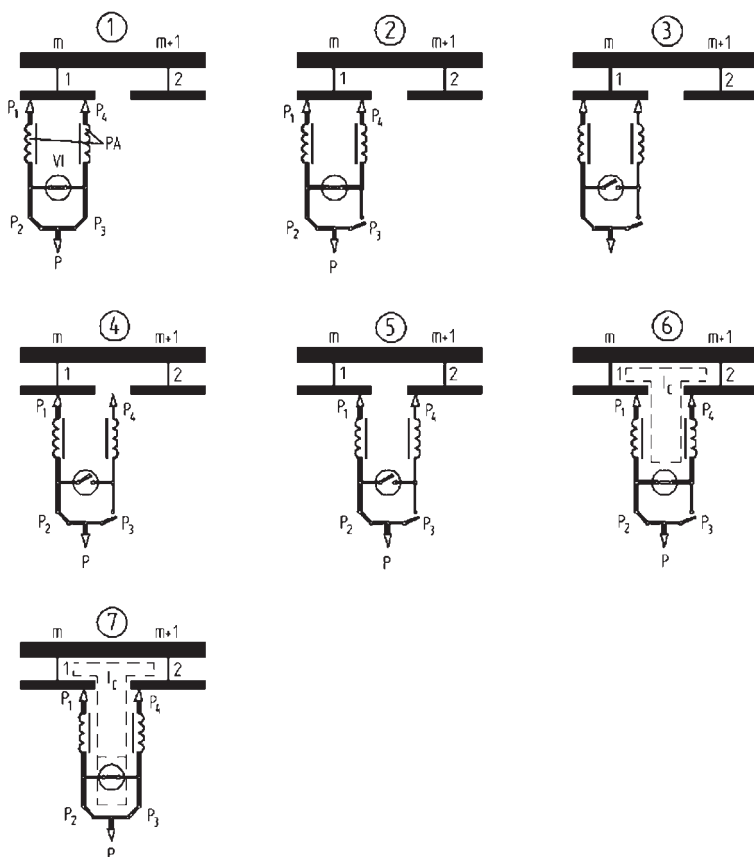
Fig. 25 Switching sequence of resistor type OLTC VACUTAP® VR

Design Concepts of Today's On-Load Tap-Changers

4.2.4.3 Switching Principle of a Reactor Vacuum Type OLTC – VACUTAP® RMV

The switching principle shown in Fig. 26 and 27 relates to a design which requires only one vacuum interrupter (see Fig. 17). This design utilizes the switching principle most applied today when using a reactor, which incorporates two auxiliary contacts, the "by-pass" switch contacts, to reduce the number of vacuum interrupters required to one interrupter per phase. The tap selector comprises two sets of contacts, which are operated by two separate Geneva wheels. Like any other reactor type OLTC, this tap-changer can be operated continuously on "bridging" and "non-bridging" positions. Bridging positions are those positions where the two tap selector contacts connect to two adjacent taps of the regulating winding. On non-bridging positions on the other hand, both selector contacts connect to the same tap of the regulating winding. Figure 26 shows the sequence of operation from a non-bridging position (step 1) to a bridging position (step 7). The continuation from the bridging position (step 7) to the next non-bridging position (step 13) is shown in Figure 27.

When on a non-bridging position (Figure 26, step 1) the OLTC selector contacts and by-pass contacts are closed, forming two separate current paths, each carrying 50% of the load current. The tap change operation starts with the opening of contact P3 of the by-pass switch (step 2). This action routes one half of the load current through the vacuum interrupter. Subsequently, the vacuum interrupter opens (step 3) under spring force and extinguishes the arc within the first current zero. This transfers the current flow to the P1-P2 current path and the tap selector contact P4 can now advance load free to the adjacent tap (step 4). Once it has reached its new operating position (step 5), the vacuum interrupter recloses (step 6), followed by the reclosing of the by-pass switch P3 (step 7). The OLTC is now on a bridging position. Bridging positions are characterized by a circulating current (I_c in Figures 26 and 27, step 7) that is driven by the voltage difference between the two adjacent taps and is limited by the impedance of the preventive autotransformer (reactor).



- P_1, P_4 Tap selector contacts
- P_2, P_3 By-pass switch contacts
- VI Vacuum interrupter
- P Output point
- I_c Circulating current
- PA Preventive autotransformer
- m, m+1 Tap m, tap m+1

Fig. 26 Switching sequence of reactor type OLTC with one vacuum interrupter per phase from non-bridging to bridging position – VACUTAP® RMV

Design Concepts of Today's On-Load Tap-Changers

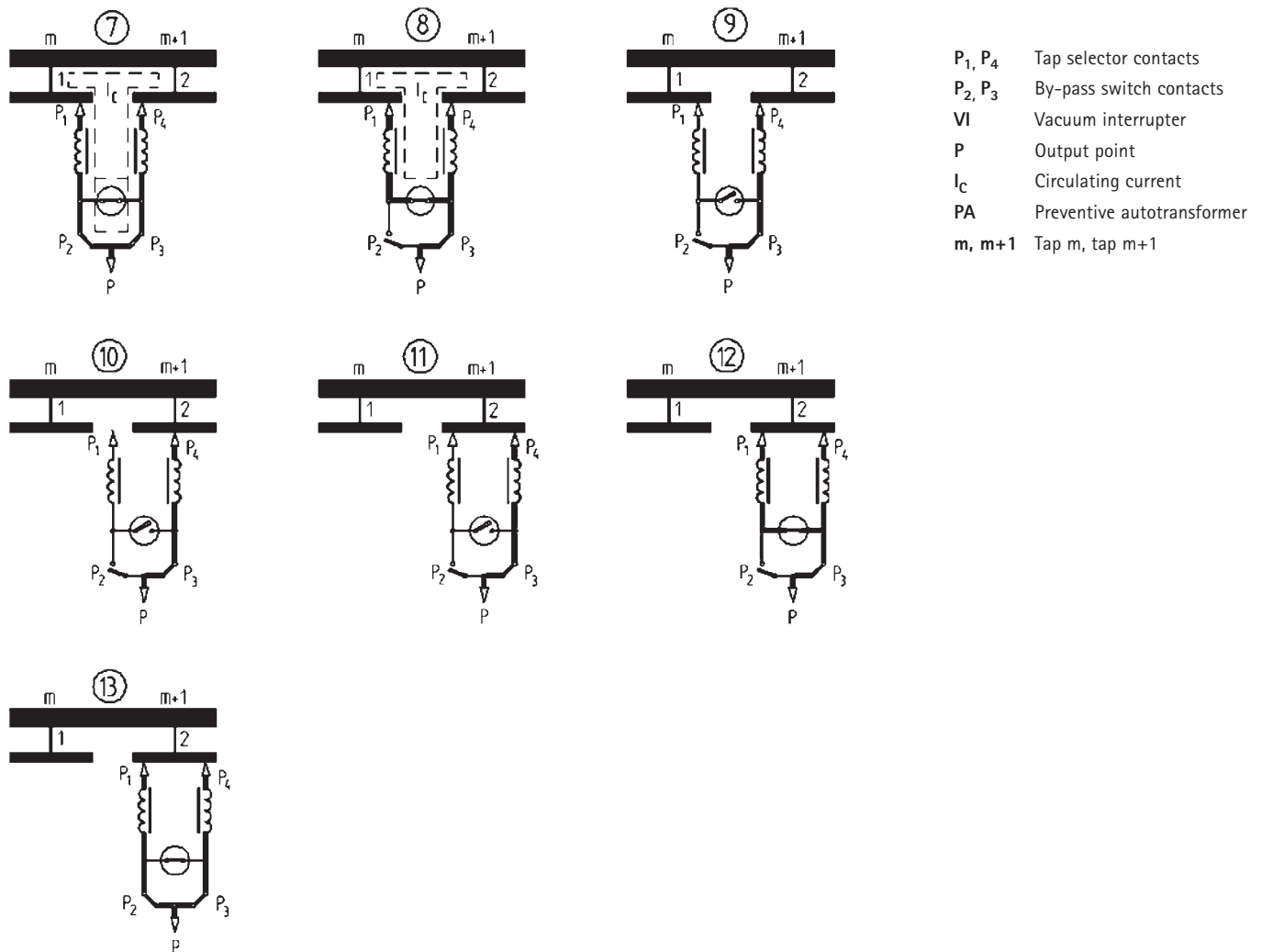


Fig. 27 Switching sequence of reactor type OLTC with one vacuum interrupter per phase from bridging to non-bridging position – VACUTAP® RMV

Continuing to the following non-bridging position, the tap change operation starts now with the opening of the P_2 by-pass switch contact (Fig. 27, step 8). The current now routed through the vacuum interrupter is again extinguished within the first current zero after the opening of the interrupter (step 9). The P_1 selector contact can now move load free to the adjacent tap (step 10). Once the tap selector P_1 reaches its next operating position (step 11), the tap change operations is completed with the reclosing of the vacuum interrupter (step 12) and by-pass switch contact P_2 (step 13).

5. Maintenance Strategy and Operating Costs Example for Resistor Vacuum Type OLTCs – VACUTAP® VR and VV

Power transformers equipped with OLTCs are main components of electrical networks. Therefore, the operational reliability of these transformers and their OLTCs is of high importance and has to be kept at a high level during their entire life span.

As shown above, the vacuum type OLTC represents a big improvement for the tap-changer technology, however, the vacuum OLTC is still a mechanical switching equipment and needs its maintenance.

The principle of a preventive, i.e. periodic maintenance strategy for oil type on-load tap-changers, is based on the time in service or the number of operations, whichever comes first. To the Reinhausen vacuum type OLTCs – immersed in transformer mineral oil – applies only the number of operations. Time-based maintenance is not required anymore.

Except for special applications, the intervals for oil type OLTCs in star-point application used in network transformers is typically 7 years or 50,000 to 100,000 operations. For this application the time in service is the decisive factor. Considering a transformer lifespan of 40 years, 5 maintenance interventions are required for the OLTC (see Fig. 28).

The operating costs are higher when considering delta applications. Depending on conditions, e.g. application of the oil type OLTC at the line end of the winding and operation with or without an oil filter plant, between 6 to 10 maintenance interventions are necessary (see Fig. 28).

The maintenance interval for resistor vacuum type OLTCs was extended to 300,000 operations. Thus for a network transformer means maintenance-free operation during the lifespan of the transformer (Fig. 28).

The maintenance measures required are almost identical for both tap-changer types. The focus is on checks, meaning the comparison between actual and desired condition of mechanically and dielectrically stressed components.

The measures required between the maintenance interval of the vacuum type OLTCs are minimal and can be easily combined with the usual check-up on the transformer and include the following scope of work:

- Visual check of the motor drive unit
- Protection test of the protective relay of the tap-changer
- Monitoring of the tap-changer oil (the dielectric strength is the decisive criteria)
- Regular check of the breather system (Silicagel)

Beside the direct maintenance costs for the OLTC all associated expenses for handling and special equipment needs to be evaluated. Further, additional substantial savings are achieved by eliminating the need for on-line filtration systems, which are widely used today on conventional OLTCs. It cannot be overseen that an on-line filtration system does generate operating costs during the life of the transformer in addition to the startup investment.

In addition to drastic savings in maintenance and operating costs, life cycle cost considerations add several other advantages for the enduser:

- Longer, uninterrupted availability of the transformer
- Simplified maintenance logistics
- Protection of environmental and natural resources due to the reduction of oil changes, by-products and worn out contacts.

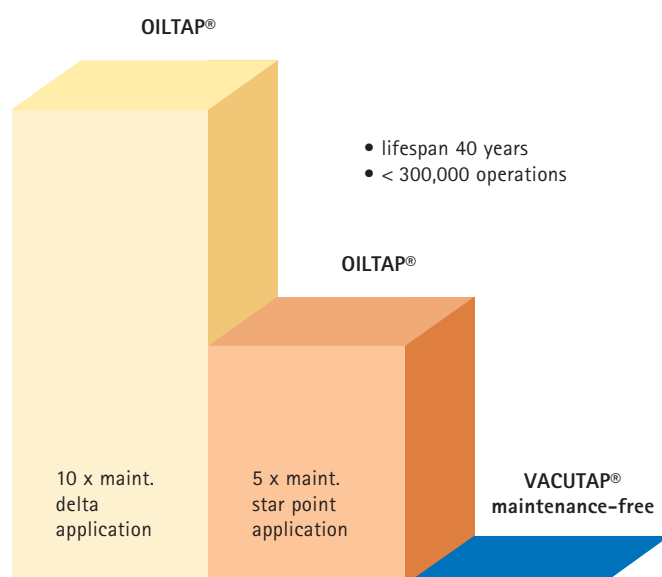


Fig. 28 Performance of maintenance during lifespan for typical network application

6. Selection of Load Tap Changers

6.1 General Requirements

The selection of a particular OLTC will render optimum technical and economical efficiency if requirements due to operation and testing of all conditions of the associated transformer windings are met. In general, usual safety margins may be neglected as OLTCs designed, tested, selected and operated in accordance with IEEE and IEC standards [4], [5], [12], [13], are most reliable.

To select the appropriate OLTC the following important data of associated transformer windings should be known:

- MVA-rating
- Connection of tap winding (for wye, delta or single-phase connection)
- Rated voltage and regulating range
- Number of service tap positions
- Insulation level to ground
- Lightning impulse and power frequency voltage of the internal insulation

The following OLTC operating data may be derived from this information:

- Rated through-current: I_u
- Rated step voltage: U_i
- Rated step capacity: $P_{st} = U_i \times I_u$

and the appropriate tap changer can be determined:

- OLTC type
- Number of poles
- Nominal voltage level of OLTC
- Tap selector size/insulation level
- Basic connection diagram

If necessary, the following characteristics of the tap changer should be checked:

- Breaking capacity
- Overload capability
- Short-circuit current (especially to be checked in case of phase shifting applications)
- Contact life

In addition to that, the following two important OLTC-stresses resulting from the arrangement and application of the transformer design have to be checked:

6.2 Potential Connection of Tap Winding during Change-Over Operation

During the operation of the reversing or coarse change-over selector, the tap winding is disconnected momentarily from the main winding.

It thereby takes a potential that is determined by the voltages of the adjacent windings as well as by the coupling capacities to these windings and to grounded parts. In general, this potential is different from the potential of the tap winding before the change-over selector operation. The differential voltages are the recovering voltages at the opening contacts of the change-over selector and, when reaching a critical level, they are liable to cause inadmissible discharges on the change-over selector. If these voltages exceed a certain limit value (for special product series, said limit voltages are in the range of 15 kV to 35 kV), measures regarding potential control of the tap winding must be taken.

Especially in case of phase-shifting transformers with regulation at the line end (e.g. Fig. 9), high recovery voltages can occur due to the winding arrangement. Figure 29a illustrates a typical winding arrangement of PST according to Fig. 9. Figure 29b shows the diagram of that arrangement without limiting measures. As it can be seen, the recovery voltages appearing at the change-over selector contacts are in the range of the system voltages on the source and the load side. It is sure, that an OLTC cannot be operated under such conditions. This fact has already to be taken into account during the planning stage of the PST design [2], [3], [4], [6].

Selection of Load Tap Changers

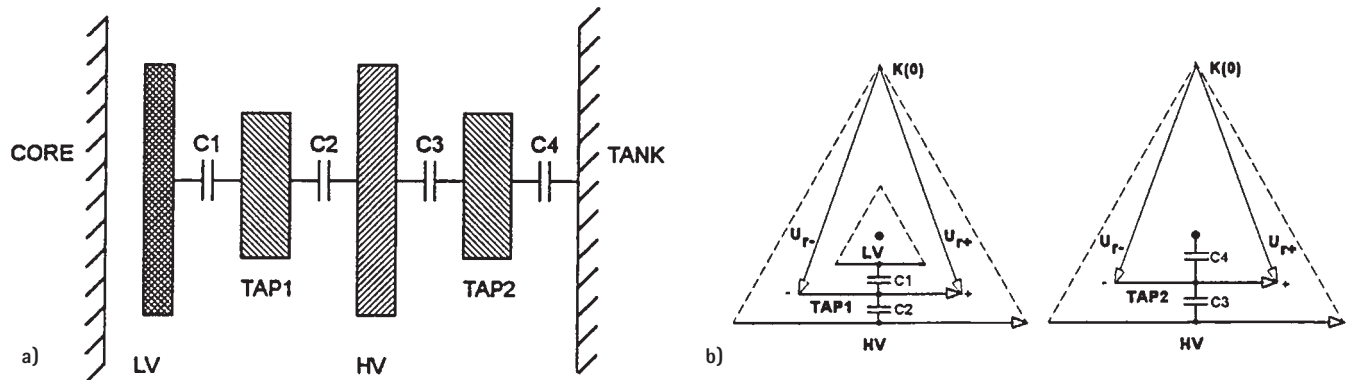


Fig. 29 Phase-shifting transformer, circuit as shown in Fig. 9

a) Typical winding arrangement with two tap windings

b) Recovery voltages (U_{r+} , U_{r-}) for tap windings 1 and 2 (phasor diagram)

There are three ways to solve the above mentioned problem:

- One possibility of decreasing the recovery voltages is to install screens between the windings. These screens must have the potential of the movable change-over selector contact 0 (Fig. 9). See Figures 30a and 30b.

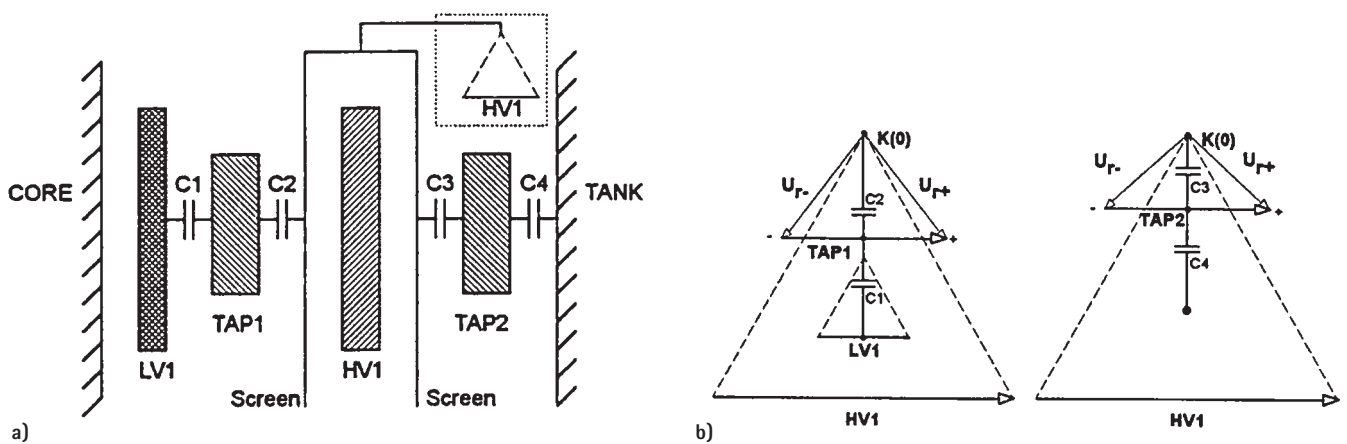


Fig. 30 Phase-shifting transformer, circuit as shown in Fig. 9

a) Winding arrangement with two tap windings and screens

b) Recovery voltages (U_{r+} , U_{r-}) for tap windings 1 and 2 (phasor diagram)

Selection of Load Tap Changers

- The second possibility is to connect the tap winding to a fixed potential by a fixed resistor (tie-in resistor) or by an resistor which is only inserted during change-over selector operation by means of a potential switch. This resistor is usually connected to the middle of the tap winding and to the current take-off terminal of the OLTC (Fig. 31).

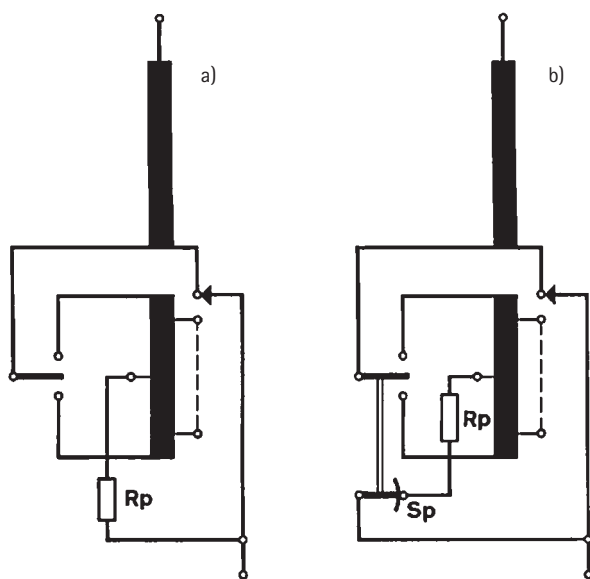


Fig. 31 Methods of potential connection (reversing change-over selector in mid-position)

a) Fixed tie-in resistor R_p

b) With potential switch S_p and tie-in resistor R_p

- The third possibility is to use an advance retard switch (ARS) as change-over selector (Fig. 32). This additional unit allows the change-over operation to be carried out in two steps without interruption. With this arrangement, the tap winding is connected to the desired potential during the whole change-over operation. As this method is relatively complicated, it is only used for high power PSTs.

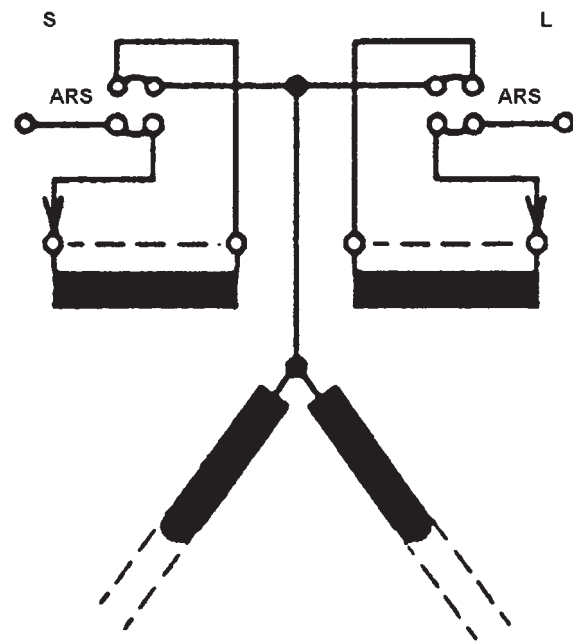


Fig. 32 Phase-shifting transformer – change-over operation by means of an advanced retard switch

The common method for the potential connection of tap windings is to use tie-in resistors. The following information is required to dimension tie-in resistors:

- All characteristic data of the transformer such as: power, high and low voltages with regulating range, winding connection, insulation levels
- Design of the winding, i. e. location of the tap winding in relation to the adjacent windings or winding parts (in case of layer windings)
- Voltages across the windings and electrical position of the windings within the winding arrangement of the transformer which is adjacent to the tap winding
- Capacity between tap winding and adjacent windings or winding parts
- Capacity between tap winding and ground or, if existing, grounded adjacent windings
- Surge stress across half of tap winding
- Service and test power-frequency voltages across half of the tap winding

Selection of Load Tap Changers

6.3 Effects of the Leakage Impedance of Tap Winding / Coarse Winding during the Operation of the Diverter Switch when Passing the Mid-Position of the Resistor-Type OLTC [6].

During the operation of the diverter switch (arcing switch) from the end of the tap winding to the end of the coarse winding and vice versa (passing mid-position, s. Fig. 33a), all turns of the whole tap winding and coarse winding are inserted in the circuit.

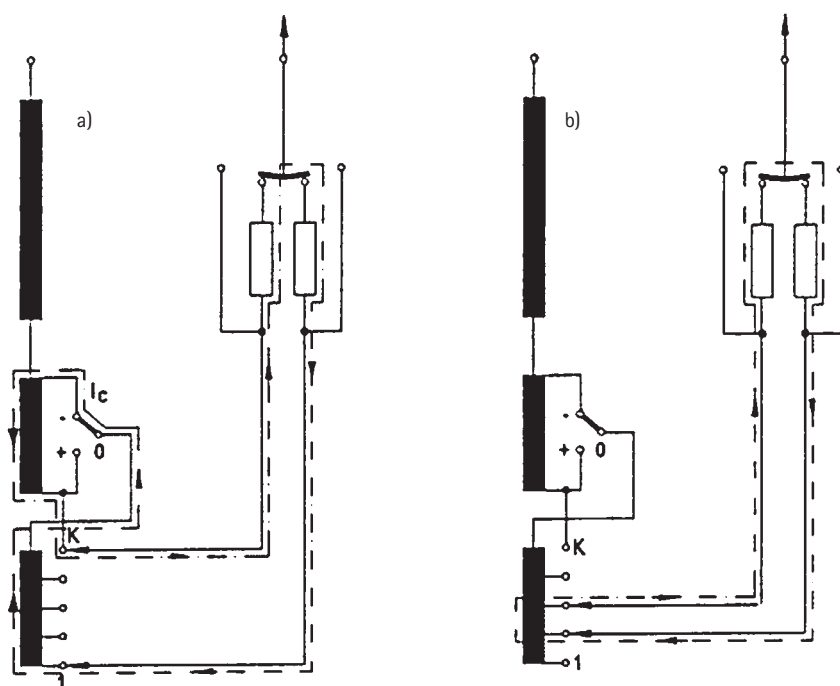


Fig. 33 Effect of leakage impedance of coarse winding / tap winding arrangement

a) Operation through mid-position

b) Operation through any tap position beside mid-position

This results in a leakage impedance value which is substantially higher than during operation within the tap winding where only negligible leakage impedance of one step is relevant (Fig. 33b). The higher impedance value in series with the transition resistors has an effect on the circulating current which is flowing in opposite direction through coarse winding and tap winding during the diverter switch operation.

Consequently a phase shift between switched current and recovery voltage takes place at the transition contacts of the diverter switch and may result in an extended arcing time.

In order to ensure optimal selection and adaptation of the OLTC to these operating conditions, it is necessary to specify the leakage impedance of coarse winding and tap winding connected in series.



7. Conclusions

Presently available technical solutions enable the production of OLTCs that are reliable and meet the same life expectancy as transformers. But still, they have to be classified as mechanical switching equipment. Today's products require little maintenance but they are not fully free of abrasion.

At the present time and for the foreseeable future, the proper implementation of the vacuum switching technology in OLTCs provides the best formula of quality, reliability and economy achievable towards a maintenance free design. The vacuum switching technology entirely eliminates the need for an on-line filtration system and offers reduced down-times with increased availability of the transformer and simplified maintenance logistics. All these together translate into substantial savings for the end-user.

Dieter Dohnal was born in Augsburg, Germany on October 31, 1951. He received the M. Sc. degree in Electrical Engineering from the Technical University Carolo-Wilhelmina of Braunschweig, Germany in 1975 and his Dr.-Ing. degree in Electrical Engineering in 1981.

After joining Maschinenfabrik Reinhausen in Regensburg, Germany in 1981 as Manager of the Design Department, he was transferred as Engineering Manager to Reinhausen Manufacturing, Humboldt, TN, USA for two years in 1987. In 1990, Dr. Dohnal became Head of Research & Development at Maschinenfabrik Reinhausen and has been Director of Engineering and R & D since 1998.

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