Tap-changer know-how

Enhancing the switching capacity of change-over selectors with minimized gas production

1. General

Regulated power transformers are equipped with a regulating winding with multiple taps which are connected to a tap-changer to adjust the transformer ratio. On-load tap-changers (OLTCs) are used if the ratio shall be changed while the transformer is under load. These tap-changers consist of a tap selector which connects two adjacent taps of the regulating winding and a diverter switch which performs the load switching operation between the two selected taps without interrupting the load current. The tap selectors often feature a change-over selector to reverse the polarity of the regulating winding or to add or bypass a coarse tap winding. The change-over selector can only be operated in the mechanical mid-position of the tap selector. At this position, the load current flows through the tap selector terminal which is connected to the end of the main winding. The regulating winding and the change-over selector are in no-load condition then.

When the change-over selector is operated, the regulating winding (and so the +/- contacts of the change-over selector) take

> **Increasing transformer ratings require ever increasing optimization of transformer windings design, putting tap-changers under more and more severe operating conditions**

a floating electric potential. The floating potential is now determined only by the capacitive coupling to the neighbouring winding(s) and the transformer core or tank wall (both earthed), see Fig. 1 as an example.

The capacitive current which must be broken and the recovery voltages on the open change-over selector contacts so generally depend on the voltages of the windings adjacent to the regulating winding, the length and position of the regulating winding, the geometric winding arrangement and the ratio between C_1 and C_2. They can reach values which cause switching sparks or low-energy arcs. Even if there are no methods to reduce the capacitive current for a given winding arrangement, measures can be applied to reduce the recovery voltages and minimize the gas production which is caused by the switching sparks/arcs. They will be discussed in the following.

2. Calculations

First, the capacitances C_1 and C_2 must be determined. Due to the typical cylindrical shape of the transformer windings, they can be regarded as cylindrical capacitors, and their capacitance can be calculated out of the winding dimensions; see Fig. 2. For further calculations, C_1 and C_2 are assumed as concentrated elements, with their contact points at the middle of the in-

> ## OLTCs are used if the ratio shall be changed while the transformer is under load, without interrupting the load current
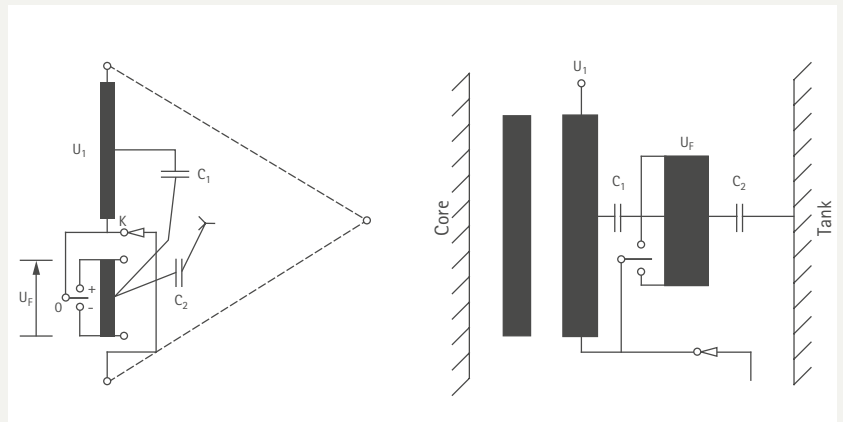

Figure 1. Capacitive coupling of the regulating winding (delta connection, reversing switch);
U_1 High voltage winding voltage
U_F Regulating winding voltage
C_1 Winding capacitance between main winding and regulating winding
C_2 Winding capacitance between regulating winding and ground

volved windings and/or to ground. This is not precise to 100 %, but gives a sufficiently good approximation. Following the example from Fig. 1, Fig. 3 shows how the capacitances "draw" the voltage vector of the regulating winding U_F to a certain location in the complex plane. The recovery voltages U_{w+} and U_{w-} on the "+" and "-"

contacts of the change-over selector can be calculated with complex mathematics. In the same way, the switched currents I_{s+} and I_{s-} can be determined.

For more complex winding arrangements, calculation of capacitances or recovery voltages and switched currents
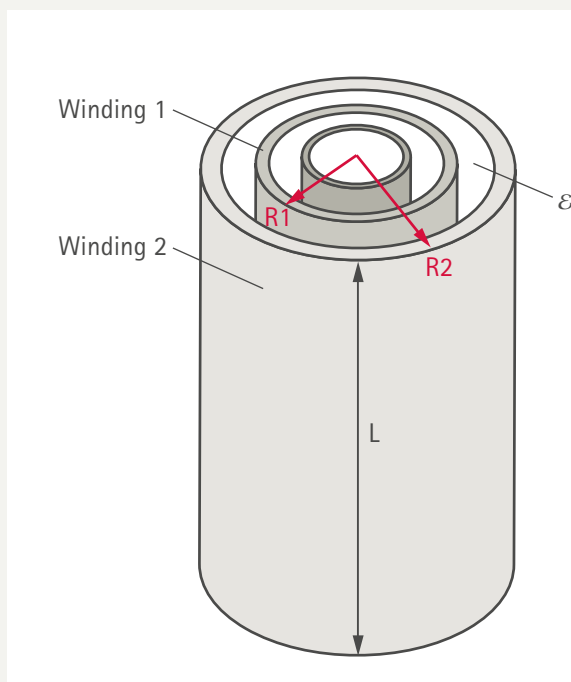

Figure 2. Cylindrical capacitor model for calculation of capacitances between windings
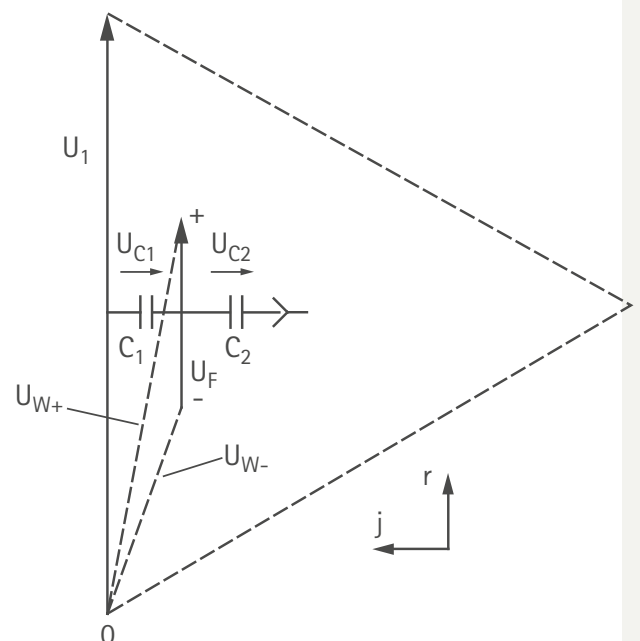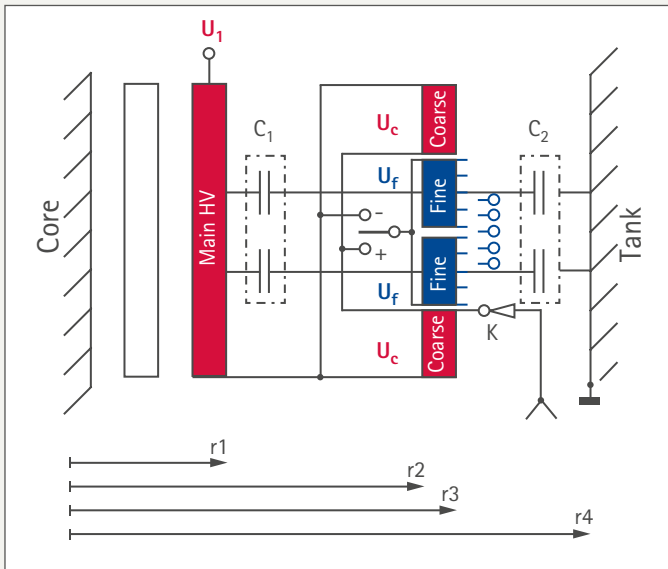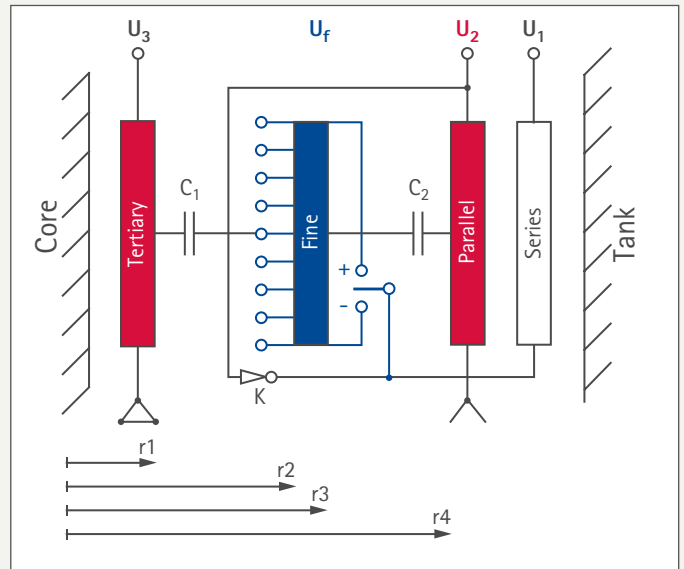

Figure 3. Vector diagram

Figure 4. a) Stacked coarse/fine tap winding arrangement   b) Autotransformer, regulating winding coupled to tertiary winding

can be quite complicated. Fig. 4a shows an example with stacked and parallel windings (coarse/fine), Fig. 4b shows an autotransformer where the regulating winding couples to a delta-connected tertiary winding. Many different winding geometries are used, some of them require consideration of a third or fourth capacitance. Such arrangements are wisely calculated by using software for electrical network calculations.

The calculation result can show values for $I_{s+/-}$ of several hundred milliamperes and up to 100 kV for $U_{w+/-}$. It must now be evaluated if the calculated values meet the switching capacity of the chosen tap selector model. All tap selector models have been tested with different loads (I_s, U_w) to determine the maximum switching capacity by evaluating the discharge (arcing) time in relation to the total switching time of the change-over selector; see Fig. 5. The admissible limit for the discharge time has been set in the range of half of the total switching time of the change-over selector (the time between electrical opening and closing of contacts). Several calculation examples for different winding arrangements with all formulae can be found in [1], pages 145ff.

3. Effects of arcing by change-over selector operation

Breaking capacitive currents of hundreds of milliamperes followed by recovery voltages of several ten kilovolts causes switching sparks or low-energy arcs. These sparks or arcs cause free gases of a few milliliters which fully dissolve in the oil. The typical composition of gases is shown in Fig. 6. The dominating gas is H_2, followed by some C_2H_2 and CH_4. The H_2/CH_4 ratio in this example is calculated to 4.74, which is in the range for low energy discharges, acc. to IEC60599. Similar values were recorded by DGA from tap selectors in field service. Overall, the H_2/CH_4 ratio can appear in the range of 4-30 – which identifies the discharges as discharges of low energy, sparks or partial discharges.

The amount of gases depends not only on the absolute values for I_s and U_w but also on the phase angle between U_w and I_s, and on the contact opening speed. In case of high I_s and U_w values, the arcing/sparking sound can be audible outside the transformer. Usually it is a short, sharp, "spiky" sound; for stronger switching arcs it changes to a bright sound, similar when hitting a hammer on a (dampened) steel plate. The sound can be scary – but it is definitely harmless.

The question is now, if and how these gases can influence transformer DGA. Users are very sensitive on acetylene (C_2H_2) in the transformer oil, as it is usually an indication for serious (and unwanted) arcing. So it is necessary to give an estimate. During the lifetime of a transformer (with tap-changer), the number of change-over operations is usually low. One can say that less than 1/10 of all OLTC operations are change-over operations. Assuming 5,000 OLTC operations per year (which is an average value for network transformers), this means that one or two change-over
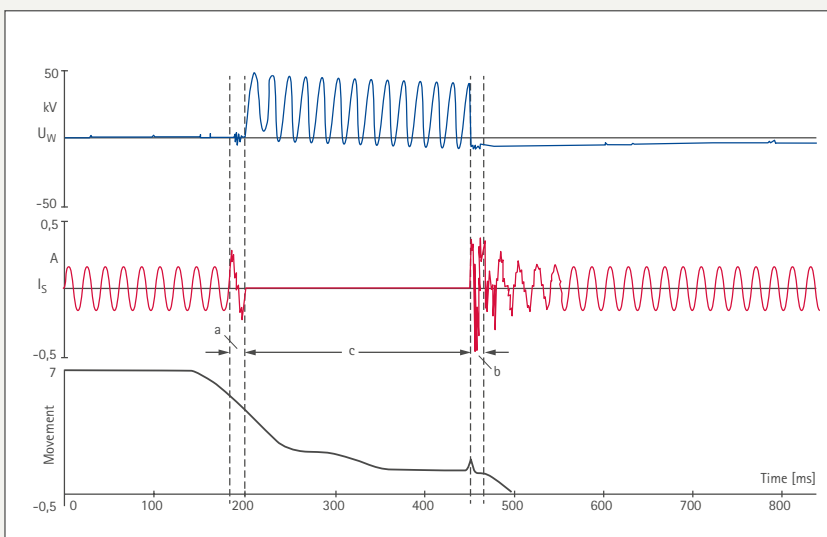

Figure 5. Discharge times (a, b) versus total switching time (a+b+c) of change-over selector

operations per day are performed. In many cases, the number will be less, because only a part of the available regulating range is used, often only either on the "+" side or only on the "-" side. U_w and I_s are usually far below the admissible limits and so will only cause a spark which causes only negligible amounts of gas. Additionally, dissolved gases get continuously lost, either via the breather (in free-breathing systems) or through gaskets or smallest leakages which are always present (relevant for gas loss in closed systems). As a result, C_2H_2 will not be detectable in most of all applications. So, sparking or arcing on the change-over selector is usually not a cause for concern. In rare cases, when high U_w and I_s are combined with a high number of change-over operations, C_2H_2 can be visible in the transformer DGA with a low single digit value which stays fairly constant. It is in the range of 1-2 ppm at maximum.

When the tap selector is mounted in a separate selector compartment, higher values of ca. 20 ppm C_2H_2 have been reported. This can simply be explained by the much lower oil volume in the selector tank (approximately 4,000 liters for a single phase transformer), which is separated from the oil in the main tank.

4. Countermeasures

With increasing transformer ratings, the winding designs of modern transformers are more and more optimized and the dimensions narrowed. As a result, the ca-

Figure 6. Typical composition of gases produced by arcing/sparking of the change-over selector

Switching sparks cause free gases of a few milliliters which fully dissolve in the oil

pacitances between the windings are increasing. This leads to higher currents I_s. Increasing system voltages and enhanced regulating ranges lead to higher recovery voltages U_w. Both parameters promote the increase of the arcing/sparking activity, which in turn leads to higher gas production. Regarding current HVDC projects in China, transformer ratings, system voltages and the kV regulating range have reached a level which drives the switching capacity of the change-over

selector of current OLTC models beyond their limits [2]. To avoid a short-circuit of the regulating winding (which definitely would cause serious damage to the transformer and tap-changer), measures are necessary – either by reducing U_w (the main influence factor for the arcing time), or to enhance the switching capacity of the change-over selector.

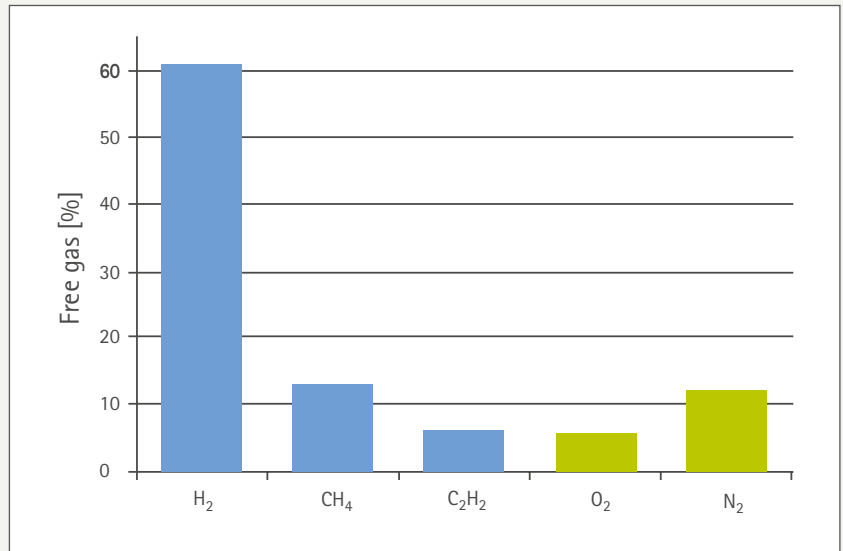Additionally, the increasing sensitivity of DGA equipment aggravates the problem.
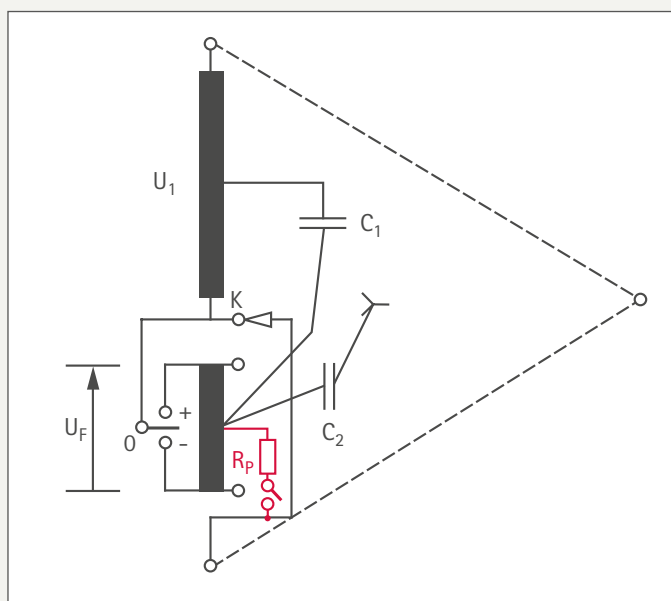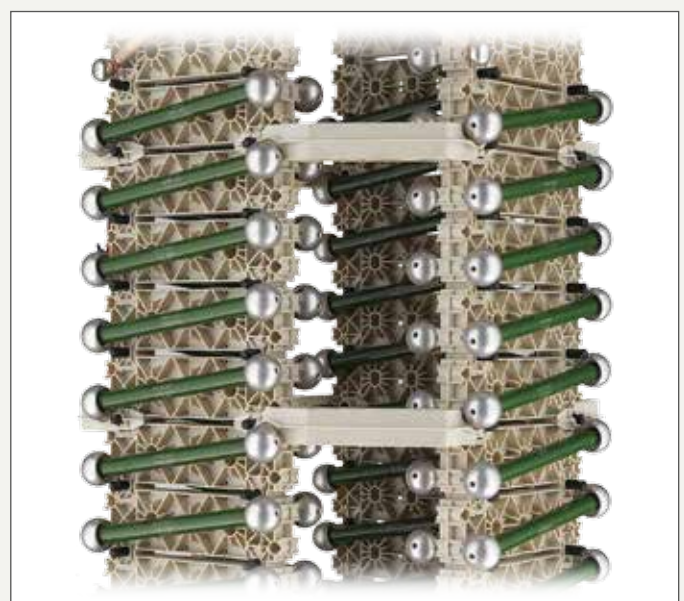

Figure 7. a) Additional tie-in resistor and potential switch

b) Stack of tie-in resistors in new RD tap selector model

The generation of arcing or sparking gases can be minimized when the contact opening speed of the change-over selector is significantly increased

While a few years ago, the accepted limit of quantification for C_2H_2 was 1 ppm, now values of 0.1 ppm can be measured reliably and with high reproducibility. Especially for HVDC applications in China, gas analyzers with very high sensitivity and precision are used to detect irregularities during the commissioning process of new equipment. C_2H_2 values in the transformer oil higher than 1.0 ppm are regarded as critical.

To meet these challenges, different measures are available which can be applied depending on the individual needs.

4.1. Tie-in resistors / Potential switch

The most common measure is to add a "tie-in" resistor which prevents the regulating winding from floating. This ohmic resistor shows a value of some ten to hundred kiloohms and is usually connected to the middle of the regulating winding and the take-off terminal of the tap-changer; see Fig. 7a. It usually consists of more than one ceramic high-power resistors which can be connected in series and in parallel (Fig. 7b). They reduce the recovery voltage U_w and so reduce the gas production. This is also audible: the sound is turned down, which indicates a reduced arcing activity. On the other hand, I_s is slightly increased.

The resistors can be connected to the tap winding either permanently or via an additional potential switch. Both variants have their drawbacks: while permanently connected resistors create additional losses depending on the tap position, a potential switch creates an additional amount of gas during operation. Nevertheless, the amount of gases created by the potential switch is very low compared to the gases produced by the change-over selector itself. The design of a tie-in resistor must be calculated individually for a given application, considering thermal and electrical limit values.

In some cases, it may be adequate to connect the tie-in resistor not to the middle of the regulating winding, but to a different tap (off-center connection). This is done if U_{w+} and U_{w-} strongly differ. Off-center connection of the tie-in resistor aligns the absolute values for U_{w+} and U_{w-} (and I_{s+}, I_{s-} with them).

4.2. Separate selector compartment

Using a separate selector compartment is a concept which originates from the design of compartment type tap-changers commonly used in the U.S. and U.K. These OLTC types accommodate the tap selector and change-over selector inside the OLTC oil compartment. The leads from the tap winding are connected to the tap-changer via a barrier board which strictly separates the tap-changer oil from the transformer oil. If in-tank type OLTCs with diverter switch and separate tap selector shall be used, the transformer is equipped with a separate housing for the tap-changer, which is constructed as a "back-pack" at the front wall of the transformer. The advantage of such construction is an undisturbed transformer oil DGA and the possibility to monitor the gas production of the tap selector separately. The disadvantage is that an extra panel board is needed which features a feedthrough for all leads between the tap-changer and the regulating winding.

4.3. Double reversing change-over selector (ARS)

The double reversing change-over selector (also called "Advanced Retard Switch", ARS) works slightly different to a reversing switch, as it uses two reversing contacts connected in parallel which feature three operating positions. It avoids floating of the regulating winding because the regulating winding is always connected to the end of the main winding during the course of the reversing process. A detailed description of the operating principle can be found in [1], p. 175ff. Because the load current flows through the ARS
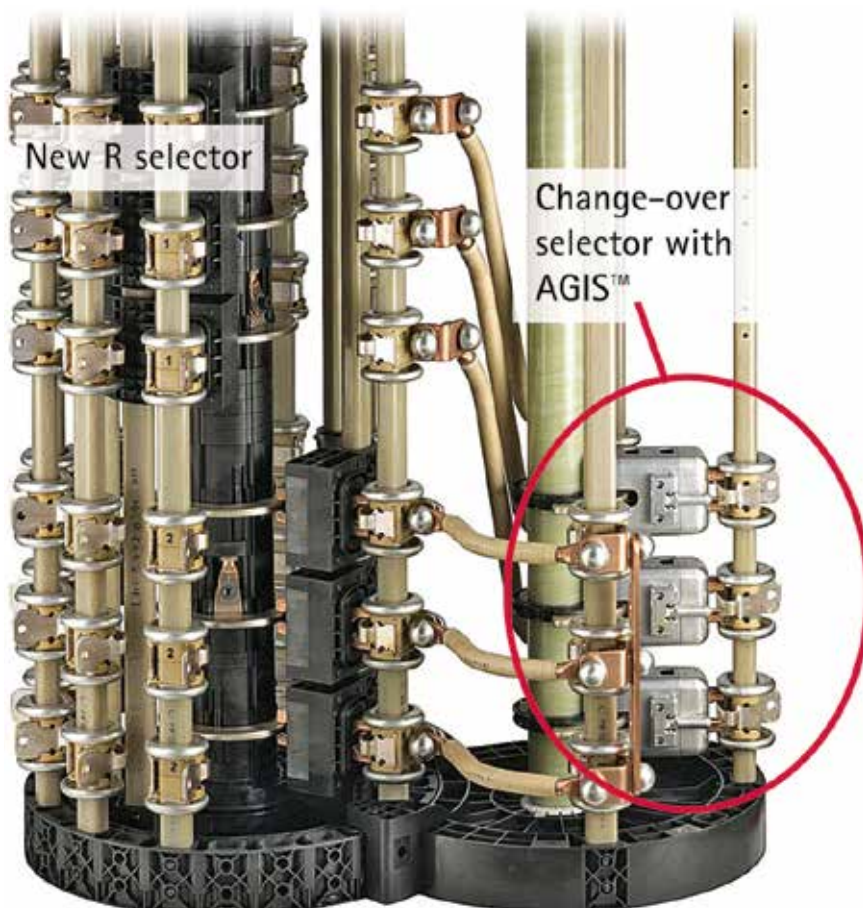

Figure 8. "New R selector" with AGIS™ (snap contact) on change-over selector

when operated, there is some current commutation between the different current paths which can cause some sparks. But as the inductive loops are usually very small, the spark energy and its gas production can be neglected. ARS double reversing switches are often used in phase-shifter transformers with regulation at the line end [3] and sometimes in HVDC converter transformers.

Please note that this solution is not suitable for coarse/fine tap arrangements.

4.4. Capacitive control

When looking on Fig. 3, it is obvious that the recovery voltages U_{w+}, U_{w-} can be reduced if the potential of the regulating winding is drawn to the end of the main winding U_1. This requires a large capacitance between the end of the main winding and the center of the regulating winding. By adding a metallic shield between the regulating winding and the neighbouring winding, C_1 can be defined in the desired way. The shield must be connected to the desired potential, which, in our example, is the end of the main winding (change-over selector contact "0"). Shields usually increase the diameter of the winding, but can fully take over the role of a tie-in resistor. Important is a balance between low recovery voltages U_{w+}, U_{w-} (which means a large capacitance C_1) and low switched currents I_{s+}, I_{s-} (which requires small capacitances). This measure is mainly used in phase-shifter transformers.

4.5. AGIS™ (Active Gas Inhibition System)

A new generation of tap selectors ("new R selector"; see Fig. 8) features an optional "Active Gas Inhibition System" (AGIS™), which is an additional spring-loaded snap contact (Fig. 9). It first delays the contact opening when the change-over selector starts moving, but then it extremely accelerates the switching operation. Switching as fast as possible is an old and proven principle to minimize arcing activity. It can be found in circuit breakers as well as in home light switches or automatic fuses. Accelerating the switching speed leads to very short arcing/sparking times, so that, in combination with the new tap selector design, a switching capacity of the change-over selector of 50 kV / 700 mA is achieved. By applying this additional contact, the gas production of the change-over selector is reduced by approximately 90 %. Also the arcing sound is minimized. Tests have shown that free gases were not detectable.

Using this design, tie-in measures can be avoided in many cases. For the remaining cases, economic considerations will often suggest an additional potential switch which again increases the gas production. Studies on HVDC applications in China [2] have shown that the total gas pro-
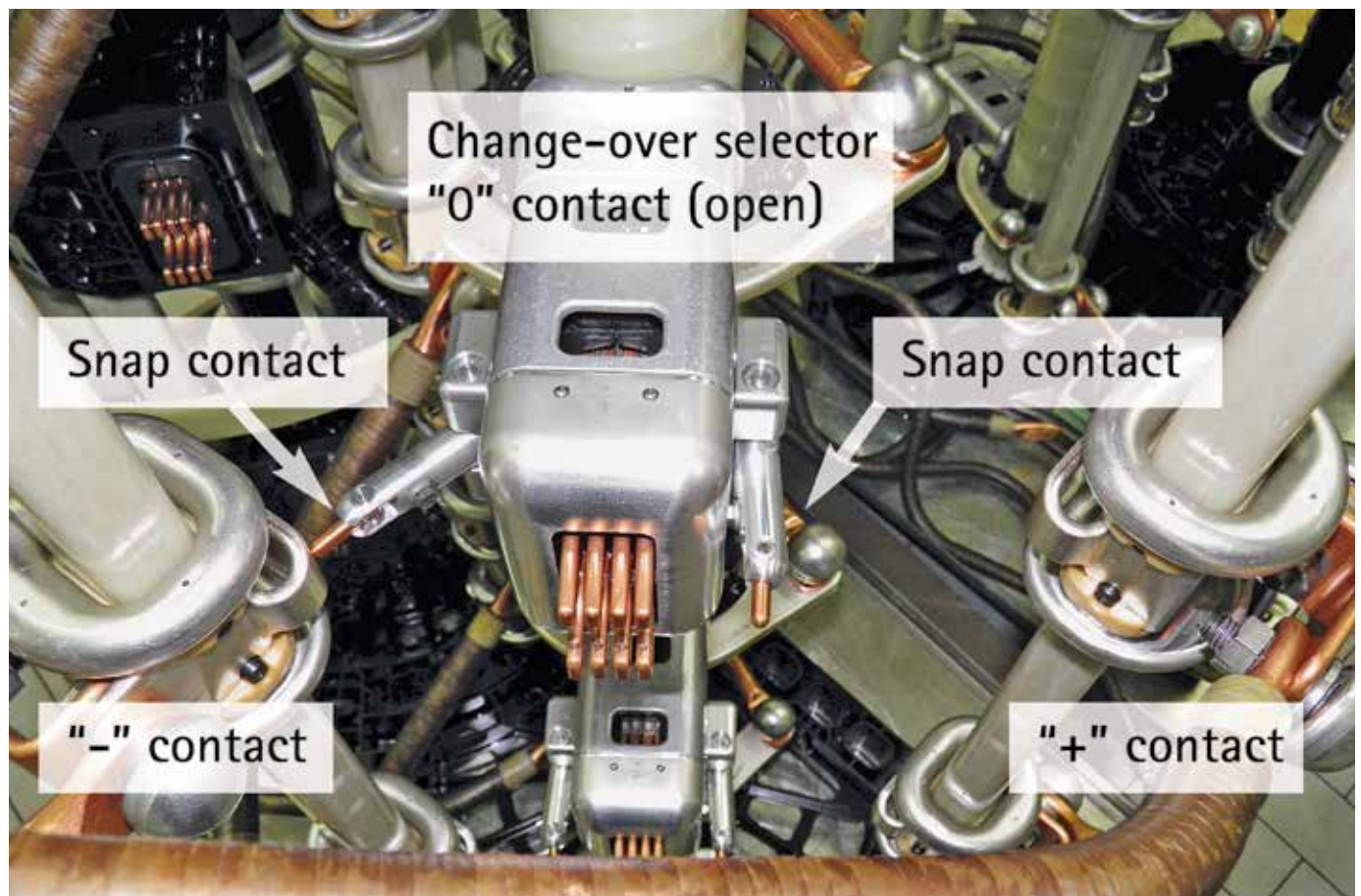
Figure 9. Change-over selector with AGIS™

duction of the change-over selector with AGIS™ plus potential switch is about 70 % lower than without AGIS™ – which still is a significant improvement.

5. Conclusion

The potential connection of the regulating winding is a complex topic which necessitates an individual evaluation for each application. The most common and accepted method to reduce the recovery voltages on the open change-over selector contacts is to use tie-in resistors. The generation of arcing or sparking gases can be minimized when the contact opening speed of the change-over selector is significantly increased. To achieve this, the new generation of MR tap selectors can be equipped with an additional snap contact. When using this, it can be assumed that the transformer DGA will not be influenced by the change-over operation.

Bibliography

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[2] D. Shen, M. Späth, *Technical challenge of EHVDC development on On-Load Tap-Changers in Converter Transform-* *ers,* CIGRE SC A2 Colloquium, Shanghai, China, Sept 2015

[3] A. Krämer, J. Ruff, *Transformers for Phase Angle Regulation Considering the Selection of On-Load Tap-Changers,* IEEE Transactions on Power Delivery, Vol. 13 (1998) No. 2, pp. 518-525

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