

# Suppression of transients across the tap windings of an auto-transformer

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For the energy transfer between the various voltage levels of the Eskom national grid, auto-transformers are mainly installed. These auto-transformers are interfaced with the distribution network.

The specific constant impedance characteristics of these auto-transformers require a very special winding arrangement: core; low voltage winding; tapping winding; common winding; and series winding as shown in Fig. 1 [1]. The main reason for adopting the constant ohmic impedance characteristics for all standard transformers was to ensure that there is a constant fault contribution, to the low voltage bus bar regardless of tap position. By specifying this narrow impedance slope the manufacture of autotransformers were required to use line-end tap changers. This winding arrangement results in a high voltage stress area, between the bottom end of the tapping winding and the bottom end of the LV winding and common winding known as the "voltage knife effect", containing high-risk elements for oscillation failure under through faults and overvoltage condition [1].

When the resonant frequencies of the line and the transformer match, very high voltages appear on the secondary terminals of the transformer. These voltages occur in the feeders connected to the secondary side of the transformer. They include 66 kV, 88 kV and 132 kV. Tap windings are therefore subjected to high oscillation. The authors will pay attention to the protection of the tap windings by means of ZnO varistors, an excellent non-linear resistor, connected in parallel with the tap windings leads [2].

### Causes and effects of transient voltage stresses

The transients may be as a result of lightning strikes, switching operations and ground faults, and chopped by an external surge arrester. Oscillations will result when lightning surges, followed by a ground fault, excite the natural frequencies (at the power frequency range and also higher frequencies) of the tapping winding and the main transformer windings. The uneven transient voltage distribution resulting from the transformer winding arrangement has also been

identified as a major risk element under ground fault and overvoltage conditions resulting in the so-called "voltage knife" effect in the windings [2], [3], [4].

The tap winding insulation on a number of existing transformers (approx. 45 units) was not designed to cater for this "voltage knife" effect due to lack of computer programs in the early days, and partly ignoring recurrent surge test (RST) measurements. These tap windings have extreme sensitive insulation requirements and are unable to control lightning impulse stresses within the winding and to ground [1]. An extraordinarily high frequency of ground faults is observed on the distribution interface especially on the medium voltage 66 kV, 88 kV and 132 kV level, and this is a major concern. The high fault frequency is due to South Africa specific service conditions (open fires, blizzards, animals (cats), birds, criminal acts). These high faults frequencies are cumulative and repetitive during auto-reclosure fault clearing.

When transient oscillations with a steep front enter from a system into a transformer, the transformer reacts as system of capacitance. The transformer oscillates towards its final distribution (inductance). The qualities of resistance, inductance and capacitance undergo material temporary changes compared with their values under normal condition. While transformer windings are generally considered merely as large inductances, they also contain capacitance distributed throughout the windings in different ways depending upon the type of coils and the arrangement of windings. At normal operating frequencies, the effect of electrostatic capacitance between turns and layers of individual coils is negligible, and as a result of this the windings act as a simple concentrated inductances giving uniformly distributed voltages. When the windings are subjected to the sudden impact of high-voltage and high frequencies, or steep-fronted waves, the effect of electrostatic capacitance in

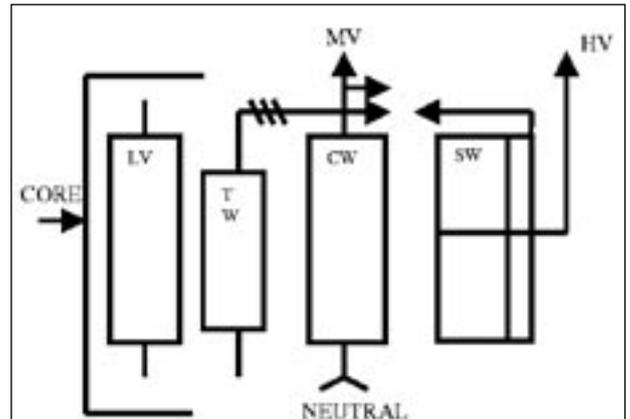


Fig. 1: Winding arrangement

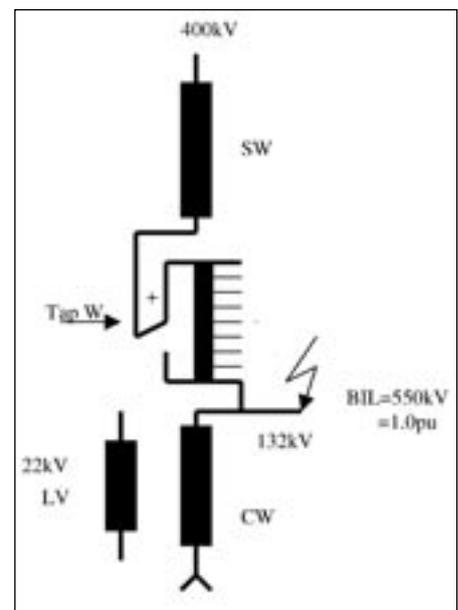


Fig. 2(a): Winding diagram

determining the initial voltage distribution becomes important, due to the fact that capacitance's which are unimportant at low frequencies may have very low impedance or even become virtually short circuits, when subjected to high frequency waves or to steep-fronted impulses. Furthermore, at high frequencies the condition of resonance may be reached for the various combinations of inductances and capacitances [5].

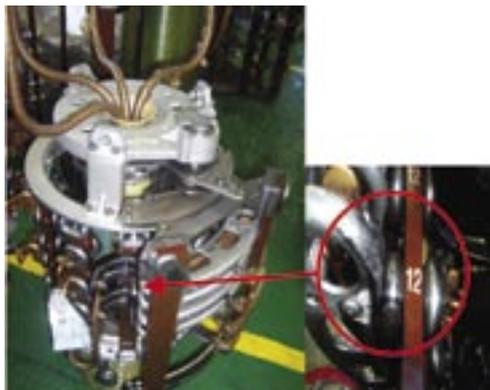


Fig. 2(b): Tap selector with flashover marks



Fig. 2(c): Collapsed Tap winding with inter-turn short circuits

These overvoltages stress the entire insulation system in many cases resulting in the dielectric break down from tap winding to ground as well as within the tap changer area, mainly the tap selector. Flashovers within the tap selector area cause internal short circuits in the tap winding. The tap winding is not designed to be exposed to internal short circuits as a result it collapses in many cases due to axial forces [3]. Due to the high frequency of ground faults and the risk elements presented by the winding arrangement in the main transmission system, damping of these oscillatory overvoltages is necessary using ZnO varistors, especially in the area of the tap winding. This will improve their condition and enhance their service performance.

#### Protection against overvoltage

Non-linear resistors inside power transformer have been in use for more than 25 years to control overvoltages caused by various system transients [6]. ZnO varistors provide protection against all kinds of overvoltages, the resonant excitation of high frequencies included.

These devices are significantly more non-linear than older silicon carbide discs. The industry began to replace them and the modern units offered a superior protection. These are nonlinear circuit elements, whose resistance is dependent on the applied voltage. Simply put, as the voltage increases, the resistance decreases, allowing more current to flow. Zinc oxide varistors are the newest type developed, and they are exceptionally non-linear. Below a certain threshold voltage, their resistivity is very high, At a voltage slightly above the threshold level, the resistivity suddenly falls to only a few ohm-cm. The resistivity of the grain boundary itself is very high and has the desired non-ohmic properties. The total breakdown voltage of the final product is directly proportional to the number of grain boundaries, which exist between the two electrode surfaces across the tap winding [7].

ZnO varistors offer protection because as the voltage tries to rise above the threshold level, the resistance plummets and a large amount of current is passed. This action keeps the voltage to ground below the threshold level as the power is shunted through the discs. They are made to operate only during the very short time voltage transients such as during switching, lightning or high frequency transients. These are types of transients that produce the highest internal voltage stresses in the transformer, as well as the highest possibility of exciting damaging winding resonances.

It has already been established that auto-transformers with direct regulation as installed in the Eskom national grid are carrying potential risk of failure in the tap winding due to the specific winding arrangement as indicated in Fig. 1. The insulation problem is created by the so called "voltage knife" condition, which is the condition where the tap winding is located between the low voltage winding and neutral end of the common winding. Moreover, when the transformer is exposed to atmospheric overvoltages, the transient voltages of the tap winding are oscillating significantly beyond the protective level. It is extremely difficult to build in sufficient insulation to withstand the applied voltage stresses [4].

#### Methodology

A 3-phase 500 MVA, 400 - 12 x 1,25% /132/22 kV auto-transformer from Hermes substation was used. The winding arrangement and diagram of the model are shown in Fig. 1 and 2(a) respectively. The experiment is focused on the protection of the tapping winding only. The TRANEMSW program (for transient calculations) was used for simulation. Using the model transformer, assumed to be a large power transformer, lightning impulse of 550 kV was applied on the secondary side of the transformer. The transient response of the voltage across tap winding to oscillatory surges is measured with the tap winding connected and not connected with ZnO varistors.

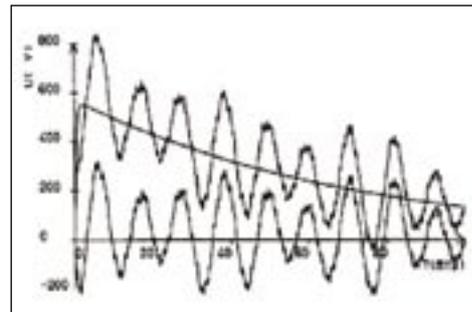


Fig. 3: Tap winding without ZnO varistor protection

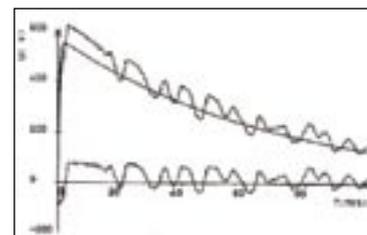


Fig. 4: Tap winding with ZnO varistor protection

The above Fig. 2(a) shows the positive extreme tap positions (+) which shows the very important basis for the consideration of transient oscillations without the protection of the tap windings by ZnO varistors. In this position the tap winding is both electrically and mechanically stressed under short circuit condition. As it can be seen on Fig. 2(b) and 2(c), the flashover has occurred in the area of the selector and the tapping winding has suffered multiple short circuits and collapsed. The transformer is currently lying in the repair workshop for major repair work of the tapping winding.

#### Results and discussion

A comparison has been made with and without ZnO varistors connected when a lightning impulse of 550 kV is applied on the secondary side of the transformer, which shows that the tap winding oscillates differently. Table 1 below shows the results. Furthermore, voltage difference oscillograms are shown in Fig. 3 and 4 respectively.

As it can be seen in Fig. 3, an impulse of 550 kV was applied on the secondary side of the transformer. It can be seen that a maximum oscillation of 840 kV was reached across the tap winding. This maximum oscillation is equal to 1,6 pu of LI. As shown in Fig. 4, when the ZnO varistors were connected across the tap winding, the oscillation was reduced to 622 kV, which is equal to 1,1 pu of LI. At 110% operating voltage, enough disks should be installed to limit the ZnO voltage to 1440 V per disk for n disks between the connections, and to 1920 V per disk for n-1 disks, to allow for safe operations if one disk should fail. A minimum of two disks should be used between lead connections. Based on the design when

calculating the voltage that appears across the portion of winding shunted by ZnO varistors during a short circuit on the system, it should not be higher than the one-minute power frequency voltage withstand, i.e. not more than 2700 V per disk. Under switching surge conditions, the ZnO-blocks should withstand a switching surge voltage of at least 2,3 times the characteristic voltage of the ZnO block, otherwise distortion will occur. Furthermore, for lightning impulse protection, the protective level crest value of the ZnO-blocks at 10 kA 8/20  $\mu$ s, shall not be higher than 2,8 times the one minute power frequency voltage withstand. The peak impulse voltage across the ZnO-blocks will be 7,57 kV per disc (crest value). The voltage per tap can therefore be calculated as follows:

$$U_i = \frac{7,57 \cdot N_d \cdot 1,3}{N_t}$$

where

$N_d$  = number of ZnO discs between terminations

$N_t$  = number of taps between terminations

## Conclusion

It can be seen from Fig. 4 that there is a huge improvement in the voltage stresses, thus confirming that parallel connection of ZnO varistors with the tap winding provides an effective means of winding protection against oscillating voltage transients. It can also be seen that "voltage knife" effect has been effectively controlled.

## Acknowledgement

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## References

- [1] Felber Engineering, "Technical expertise for the review ABB old and new designs for Transmission transformers and reactors", Internal Eskom Document, February 03.
- [2] T. Teranishi, Y. Ebisawa, T. Yanari, M. Honda, "An approach to suppressing resonance

Extreme (+) Tap position without ZnO varistor protection		
Oscillating Winding	Lightning impulse (LI) (kV)	Max oscillation (kV)
Tapping	550 (1,0 pu)	840 (1,6 pu of LI)
Extreme (+) Tap position with ZnO varistor protection		
Tapping	550 (1,0 pu)	622 (1,1 pu of LI)

Table 1: Results of the study for the extreme (+) tap position

voltage in transformer tap winding", IEEE Transactions on Power Apparatus and Systems, Vol.PAS-102, No.8, August 1983, pp2552-2558.

- [3] N Buthelezi, Willi Felber, "Voltage Knife suppression/ voltage stress relief across the tap winding in Eskom autotransformers" Internal Eskom Document, September 2003.
- [4] Willi Felber, Repair of 500MVA Autotransformer for Hermes Substation" Internal Eskom Document, January 2004.
- [5] A.C. Franklin, D.P. Franklin The J&P Transformer Book", Eleventh Edition. British: London, p528.
- [6] R. Baehr, "Use of ZnO varistors in transformers", Cigre Study Committee 12, Electra no.143 August 1992.
- [7] Frank David, "Zinc Oxide Varistors and their use inside Transformer", Winnipeg Plant. Federal Pioneer, BAT Application, April/ May 1991. ❖