THYRISTOR AIDED DIVERTER SWITCH "TADS" - A PROGRESSIVE CONCEPT FOR THE PROLONGATION OF MAINTENANCE-FREE INTERVALS OF ON-LOAD TAP-CHANGERS OF TRANSFORMERS

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ABSTRACT

On-load tap-changers in large size power transformers usually are equipped with a diverter switch. The diverter switch has relatively short maintenance intervals, especially in case of frequent tap-change operations. In this paper a hybrid switching system, combining the advantages of mechanical and electronic systems (insensibility against overloads, high reliability, low amount of maintenance), is described and discussed.

INTRODUCTION

On-Load Tap-Changers (OLTC) integrated in transformers control the voltage or power flow, or more rarely impedances (compensators).

The OLTC has to change between different taps without interrupting the load current and without causing a short circuit of the tap windings. This is realised by connecting the participating taps and the load by transition impedances (in Europe usually resistors) for a short time during the switching operation.

Except for units of lower size (e.g. selector switches), the OLTC consists of the following components:

- **a tap selector (often with an additional change-over selector):**
  It mainly consists of two subsystems per phase, one for the even taps and one for the odd. One of them carries the load current and must not be switched, the other one is off-circuit to select the next tap without load. After having selected the next tap, the tap selector stops moving and the diverter switch performs the change between the preselected taps. In the next operation cycle the roles of the even and odd subsystems are changed. Owing to the fact that there is no contact erosion and degradation of the insulating media, tap selectors do not need any maintenance for decades or about one million operations.
- **a diverter switch:**
  It carries the load current and switches it from one to the next tap selected by the tap selector. The diverter switch has to make and to break the load current and the circulating current through transition impedances and tap windings. So there is a higher need of maintenance due to arc erosion of the contacts and degradation of the oil: for network OLTCs typically every 5 to 7 years or every 50000 operations, whichever comes first.

OLTCs either are mounted within the transformer compartments or ”on-tank types”, commonly used in America. The diverter switch, in any case when arcing in oil, has its own compartment to avoid contamination of the transformer insulation oil. Nevertheless the whole system, transformer and OLTC, must be taken off service in case of maintenance of the diverter switch.

Although the conventional diverter switch of the OLTC is a mature, reliable product, there is a need of periodical maintenance. Its maintenance intervals are significantly shorter than those of the transformers it is mounted in. (Transformer: maintenance with longer interruption of service not before 10 or 15 years; OLTC: in network service typically every 5 to 7 years, in special service e.g. in furnace transformers once a year, due to high operating frequency.) In order to reduce costs and service interruptions it would be desirable, to carry out all maintenance on the OLTC only during the maintenance of the transformer.

The goal of research and development efforts is to reduce the maintenance interval (Mean Time Between Maintenance MTBM) of diverter switches. This requirement mainly depends on the erosion of the contacts caused by the switching arc. Conventional concepts to minimise the arc erosion of the contacts usually switching in oil (optimisation of contact material and geometry, movement pattern, transition impedance) are highly exhausted.

Quite a new strategy is followed by the Thyristor Aided Diverter Switch (TADS). In this concept the mechanical contacts only have to carry the continuous current, whereas for all switching operations the current is commutated to erosion-less switches (e.g. thyristors). The thyristors must be controlled by a suitable trigger unit working on high voltage potential. To release from switching load both the main and the transition contacts with just one pair of thyristors per phase, several auxiliary contacts must be provided.

In this paper concepts for thyristor aided making and breaking operation are investigated as well as concepts with thyristor aided breaking operation alone. The latter are characterised by lower stress for the thyristors, but incomplete prevention of contact erosion.

BASIC CONCEPTS

Many different suggestions have been made for reduction or elimination of contact erosion in the diverter switch. Some of them propose a static diverter switch without any moving part [1]. So the continuos current as well as an eventual short circuit current has to be carried by semiconductors, which restricts the applicability to small units. Others use the reliable and overload-insensible mechanical main contacts only for continuos currents and commutate the current to electronic auxiliary switches for the tap-change operation [2].

In this paper two concepts of the second type are discussed:

1. TADS with thyristor aided breaking and conventional making [3]
2. TADS with thyristor aided making and breaking [4]

The advantage of the first type is lower stress for the thyristors, the disadvantage incomplete reduction of contact erosion, as described later.

For one realisation of the second concept, the tap-change operation shall now be described in detail (refer to

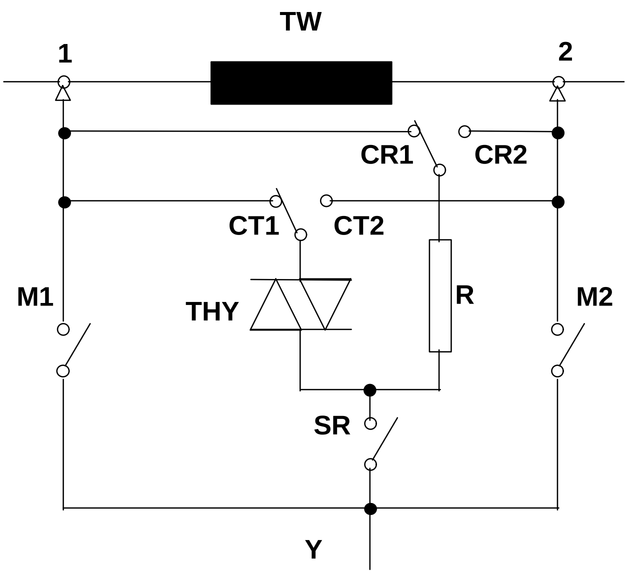

Figure 1: Circuit of a TADS for thyristor aided making and breaking

figure 1): The circuit consists of the terminals for the two preselected taps 1 and 2 of the tap winding TW, the terminal for the neutral point Y, the main contacts M1 and M2, the transition impedance R (resistor), the thyristor pair THY and the auxiliary switches CR, CT and SR.

- Figure 1 shows the circuit in the initial position for a tap-change operation from terminal 1 to terminal 2. The neutral point Y is connected to the terminal 1 by the closed main contact M1 and insulated from the terminal 2. The thyristor pair THY is not triggered at this moment.
- Auxiliary contact SR closes without load.
- THY is triggered.
- M1 is opened (thyristor aided breaking), the current is commutated to the parallel path with low impedance CT1-THY-SR.
- THY is not triggered any more. At the next current zero the conducting thyristor blocks, and the current is commutated to the parallel path with high impedance CR1-R. The current path at this moment is 1-CR1-R-SR-Y.
- CT switches from position CT1 to CT2 without load.
- THY is triggered again and connects terminal 2 with Y with the path 2-CT2-THY-SR-Y for the load current. Additionally a circulating current driven by the step voltage and limited by the transition impedance R flows from 1 to 2 trough the tap winding TW and back trough the path 2-CT2-THY-R-CR1-1.
- M2 closes without load making a parallel path to CT2-THY-SR (thyristor aided making).
- SR is opened. The load current from 2 to Y commutates to M2, the circulating current still flows.
- THY is not triggered any more. At the next current zero the conducting thyristor blocks, and interrupts the circulating current.
- CR is switched from position CR1 to CR2. The final position of the tap-change operation is reached.

Notice, that in the steady positions both terminals of the thyristor pair are connected to the same point (1-CT1-THY-R-CR1-1 or 2-CT2-THY-R-CR2-2 respectively). So eventually appearing overvoltages between the terminals of the TADS do not stress the thyristors.

THYRISTOR CONTROL UNITS

Great attention has to be paid to the control unit of the thyristors in TADS. This unit has to trigger the thyristors following the program described above. Its reliability must be guaranteed under the following special environmental conditions: electromagnetically polluted environment, oil, operating temperature range from -25°C to +100°C. The control unit must be able to supply the gates of the different thyristors on different high voltage potentials (electrically isolated from each other) with the proper amount of energy for reliable triggering at the right moment under all conditions of the thyristors, that vary on its part specially due to the wide temperature range.

Two fundamental concepts for the energy supply and synchronisation of the thyristor control units were considered:

- **Purely electronic control units:**
  In this case the two sub-control-units for each phase of the TADS have to be supplied by any transformers (inductive or capacitive) from the main circuit e.g. the actual selected tap-windings or an external auxiliary supply. In both cases the amount of energy for triggering the thyristors must be stored in the control unit in order to be able to trigger at any moment of the voltage wave. The supply of the control unit by an external supply of coarse demands its own bushings. The synchronisation of the trigger moments could be provided by mechanical auxiliary contacts or electronic switches and transducers. It depends on the mechanical movement of the actuating mechanism of the TADS's main contacts.
- **Electromechanical power supply of the control units:**
  Following this concept the energy for the thyristor control unit is converted by a small electromagnetic generator driven by the actuating mechanism of the TADS's main contacts. Moving the generator just in time, there is no need for any energy storage in the thyristor control unit. Electrical isolation of the sub-control units can be realised by separated armature windings of the generator. The basic construction of a "ROtating MAgnetic Trigger" ROMAT was considered in [5]. This type of generator is a small permanent-field machine with moving exciting magnet (of CoSm) and armature stators.

With the electromechanical power supply of the control unit, it is easy to achieve electromagnetic immunity, electrical isolation and a wide temperature range for operation. The advantage of the fully electronic control unit is avoiding moving parts.

Further components integrated in both types of control units are the circuits for controling the intensity of the trigger signals and the surge suppressors.

FUNDAMENTAL INVESTIGATIONS, EXPERIMENTAL RESULTS

In a first step the different alternatives for the main components of the TADS were investigated separately, to decide which variants should be chosen for the second step: the further optimisation of the whole system, the construction and testing of prototypes.

Long term tests on thyristors

The electronic components of the TADS, specially the thyristors, have to match certain requirements, the manufacturers has no information about. The long term behaviour of clamped thyristors in hot oil and their applicability for the TADS was investigated by the following procedures:

First the dynamic reverse- and blocking characteristic u(i) of a set of thyristors assigned for the TADS was measured at different temperatures (20°C, 100°C, 115°C and 125°C). Then the thyristors, some of them in mounting clamps, were brought into a compartment filled with oil held to a constant temperature of 90°C. (Environmental temperatures for OLTCs in oil range from -25°C to 100°C according to IEC 60214 [6].) After one year in hot oil the dynamic reverse- and blocking characteristic was measured again. The comparison of the corresponding curves showed no degradation of the characteristic.

Additionally the increase of the junction temperature due to current stress was evaluated for several parameters:

- Ambient temperatures of the thyristors: 20°C, 100°C, 115°C
- Current loads: 500 A and 1000 A, stress corresponding to a single operation of the TADS as well as stress corresponding to consecutive operations corresponding to 1000 operations of the TADS.

The rise of the junction temperature was

- about 5 K for 500 A load, about 9 K for 1000 A load for single operations and
- about 6 K for 500 A load, about 10 K for 1000 A load for consecutive operations.

It hardly depends on the ambient temperature e.g. the junction temperature at the beginning of the current stresses. This proves that the operation of the thyristors in the TADS don't cause a dangerous junction temperature (125°C).

Finally the performance of the treated thyristors under overload conditions in the TADS were tested directly: The thyristors had to switch 1000 A at 1600 V for 1000 times consecutively in oil of 100 and 115°C.

Switching tests with model switches: thyristor aided breaking only, thyristor aided making and breaking

A first test series was made to get experience, how far the erosion of the switching contacts and contamination and degradation of the oil due to arcing would be reduced by thyristor aided breaking and conventional making:

The experience can be described in a simple model: The arcing of conventional opening contacts begins at the moment of contact separation and disappears at the first current zero after having reached the necessary gap length for arc extinction. (Further parameters, if varied in ranges for application in diverter switches, have influence of lower order: contact shape, materials, current, voltage, transient recovery voltage, fluid dynamics, kinematics.) So the arcing times mainly depend on the moments of contact separation in relation to the current wave and are approximately uniform distributed in the range of 0 to 12 ms (at 50 Hz) with its average arcing time $t_{b,conv.}$ of about 5 to 6 ms.

The arcing times of thyristor aided breaking operations $t_{b,ta}$ are dependent on the current I, the circuit impedance of the commutating circuit (inductance L) and the arcing voltage U_a. They have a magnitude of 10 to 100 µs:

$$t_{b,ta.} = L * I / U_a \quad (1)$$

The arcing times of conventional making operations $t_{m,conv.}$ under normal conditions depend on the distance for disruption d_d, contact closing speed v_c and, if present, the bouncing time t_{bo}:

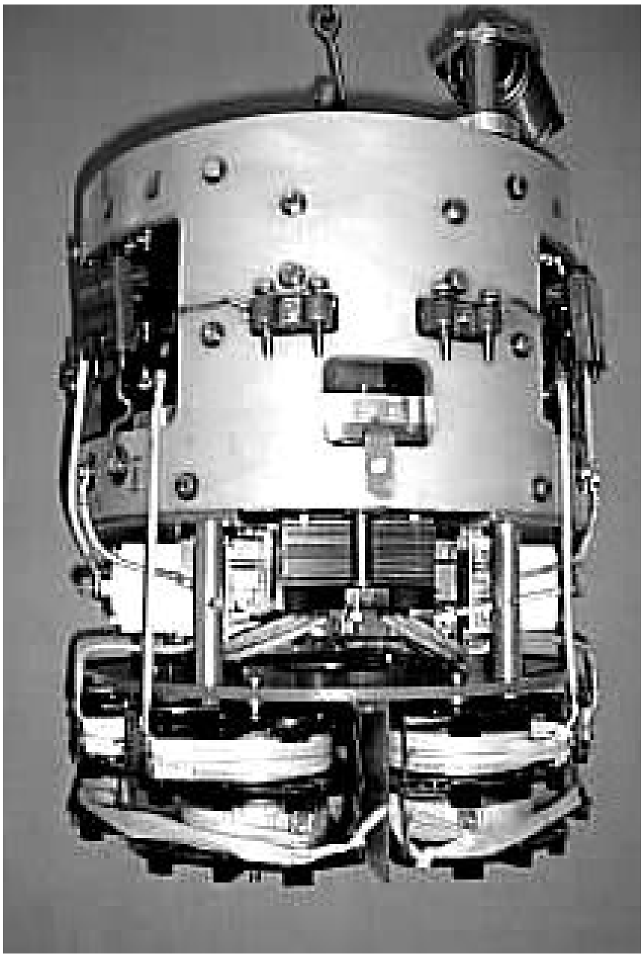

Figure 2: TADS-prototype

$$t_{m,conv.} = d_d / v_c + t_{bo} \quad (2)$$

$t_{m,conv.}$ have a magnitude of 10 to 100 µs too (further parameters usually of lower order again).
This is why the erosion of contact material and degradation of the oil could be expected to be reduced significantly by thyristor aided breaking operations alone but conventional making operations ($t_{b,conv.} + t_{m,conv.} >> t_{b,ta.} + t_{m,conv.}$).

About the first 10000 operation cycles (1600V, 1500A) of every new contact pair of a model switch with a one contact system showed arcing times as described and negligible contact erosion. But after this conditioning phase an additional mechanism started to dominate: Now the arcing time at making increased to values of 3 to 5 ms causing severe contact erosion. This effect was found to be caused by a gas layer of high pressure produced by an evaporating oil film.

At the beginning of the conditioning phase the surfaces of every contact pair do not fit together exactly. So the gas generated by the arc can escape easily. After the conditioning phase the contact surfaces fit together quite well, and sometimes also have burrs building a sealing. So the produced gas builds up a high pressure and acts against the closing force of the actuating mechanism. Evidence for this gas bulb theory was found by the fact, that in case of making with the contacts at the same voltage (1600V) but very low current (10A) the arcing times again were in the magnitude of 100 µs due to the low gas pressure. With high currents (1500A) the long arcing times returned immediately.

In the case of a conventional making and breaking contact, the surfaces are roughened by the breaking arcs. So this gas bulb effect only appears in the case of a dominating making arc.

For the reduction of the gas bulb effect suggestions were made and tested:

- contact surfaces with ribs allowing the exhaustion of the gas;
- parallel closing contacts, were the arc of the first closing contact is shorted by closing of the second contact. The second contact doesn't close at the high steady state voltage but only the arc voltage of the first closing contact. So its disruption discharge begins at a moment, were there is a smaller gap length and a smaller amount of oil between the contacts.
- modified movement of the contacts

All solutions were found to reduce the making erosion more or less satisfactory, but not economically efficient for application in the TADS.

A second test series was carried out to prove that the thyristor aided making and breaking would reduce arcing times, contact erosion and oil degradation by switching arcs to a negligible level. The investigations were made under the same conditions as above (1600V, 1500A) with the same contact arrangement in the same model switch. After 100000 operations the arcing times remained in the 10 to 100 µs-magnitude and there was negligible contact erosion except the mechanical wear.

IMPLEMENTATION AND FUTURE PERSPECTIVES

At this point a complete 3-phase TADS of the thyristor aided making and breaking type with a ROMAT thyristor control unit was designed and manufactured, with the following nominal values:

Rated step voltage U = 1300 V
Rated trough-current I = 350 A
(typical size for 50 or 100 MVA-transformers)

With this prototype (figure 2) several mechanical and electrical tests were performed. The most important was the breaking capacity test according to the standard IEC 60214 [6] "On-load tap-changers". The standard requires the performing of 40 operations with nominal step voltage and twice the nominal through-current.
The prototype passed the tests successfully.

Presently the complete type tests according to IEC 60214 of this TADS design are to be prepared (temperature rise of contacts, switching-, short-circuit current-, transition impedance-, mechanical- and dielectric tests). One part of the switching tests is the service duty test, were the diverter switch has to do 50000 operations with nominal trough-current and nominal step voltage according to the standard. For the service duty test on the TADS however, a much higher number of operations is intended.

After the prototypes will have passed the type tests, field tests with pilot applications in transformers with a high frequency of tap-change operations are intended. The implementation will be made easy by the fact that the design of the TADS guarantees geometric compatibility with standard diverter switches.

The system of the TADS can not only be a good solution for OLTCs with high operating frequency. Due to the suppression of a switching arc, the operation in alternative insulating media could be considered.

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