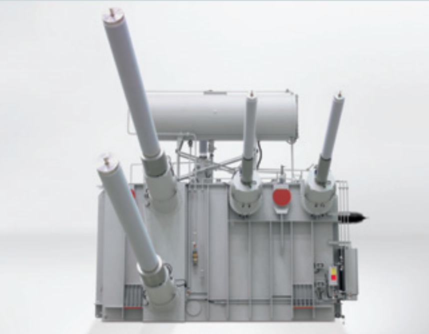

Technical paper ■ Authors: Peter Heinzig, Frank Engelskirchen

Characteristic aspects in on-site repair of HVDC-transformers and smoothing reactors

Power Transmission and Distribution

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State of the Art in HVDC Technology and On-Site Repair Aspects

Abstract: Design and manufacturing of HVDC-transformers and smoothing reactors for high DC-voltages are still something special and the number of HVDC-transformer manufacturers is limited. This paper analyses the components of HVDC-transformers and smoothing reactors in more detail and shows the influence of DC-operating conditions.

The core is very similar to the one of conventional AC-transformers since it has to fulfill the same physical tasks. For HVDC-transformers, the designer has to consider additional features like DC-currents, which can oversaturate the core and thereby might overheat it and also change completely the noise level and noise spectrum. Any kind of harmonics will influence the design of core and nearby clamping structures.

Also, the windings of HVDC-transformers are very similar to those of AC-transformers. Additional losses by current harmonics have to be considered, but its calculation is common knowledge. The evaluation of the testing procedures is not yet finally agreed upon by the experts (see also chapter 6). The valve windings are a matter of particular importance. Very high test-voltages in combination with low number of turns can be a challenge for the designer.

The insulation structure between windings and ground as well as valve side leads and bushings against ground is different from that one of AC-transformers. Field plots for AC-, DC- and polarity reversal stress describe the technical challenges in more detail.

The manufacturing process of HVDC-transformers partially differs from that one of conventional transformers. Some examples are described in this paper. The process of quality control, in particular material selection and control, component specification, and testing of components needs extra attention. The adjustment process during the design of valve leads and valve bushings under the influence of different kind of stresses and on site conditions is discussed in detail in chapter 4.

The testing of HVDC-transformers is based on standards and customer specifications. Details are discussed in chapter 6.

In chapter 9, an example for the procedure for on-site repair of a high voltage HVDC-transformer is described. The successful application of transformer technology to on-site-repair was demonstrated on a 345MVA-500kV (DC) transformer in China.

Index-Terms: DC-bushing, high voltage direct current, lead exit, magnetic core, manufacturing, testing, transformer, valve winding, on-site-repair.

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1. Introduction

The first commercially operated High Voltage Direct Current (HVDC) plants were installed approximately 40 years ago.

At that time and later in the 1970s with increasing DC-voltages, the design of transformers was more or less a research and development project. Today, after decades of operational and design experience, designers are in a better position. Computer programs for DC, DC-reversal, and conventional voltage shapes are available and there is a much better knowledge on the materials.

In spite of all improvements, the fundamental differences between HVDC and conventional AC-transformers remain:

- Insulation to ground and between AC- and valve winding has to be designed for combined AC and DC stress.
- The valve windings, especially the wye-connected valve winding with a relative low number of turns has to be tested with test-voltages determined by the protection level of the DC-side and not related to the AC-(rated)-voltage.
- Current harmonics cause losses in various parts.
- DC-currents influence the operation of the core.

In the following, some features of the design, manufacturing, and testing are discussed.

2. Magnetic Core Design

Large HVDC-transformers are usually single phase transformers. Depending upon rated voltage and transport limitations, the power per limb is in the range of 200 MVA. The core consists of two wound limbs either with two identical valve windings in parallel or with one limb in delta connection and the other one in wye-connection. The core material is usually grain oriented silicon steel. Some clients prefer surface treated steels, for example, laser scribed or plasma etched types, mainly to keep the no-load losses low.

The core stacking for HVDC-transformers is the same as for AC-transformers. Step-lap-stacking (Fig. 1) is state of the art.

However, the cooling of the core needs more attention. As a consequence of the asymmetry of the rectifier / converter station and the technical limits in controlling the remaining DC-current passing the windings, saturation of the core cannot always be prevented. A few amperes of DC-current can increase the no-load losses up to approximately 20 % and the noise by up to 22 dB.

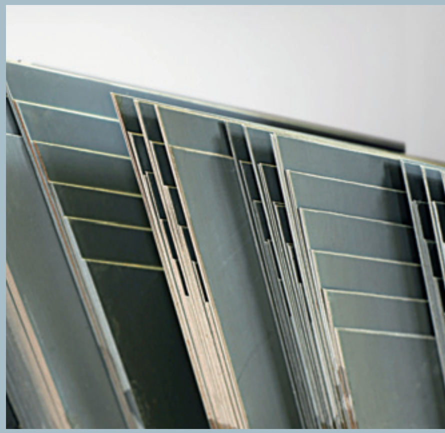

Fig. 1: Step Lap Stacking

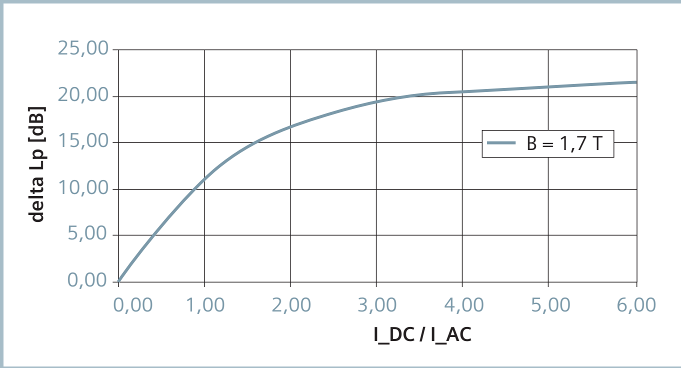

Fig. 2: Increase of no load losses under small DC-currents

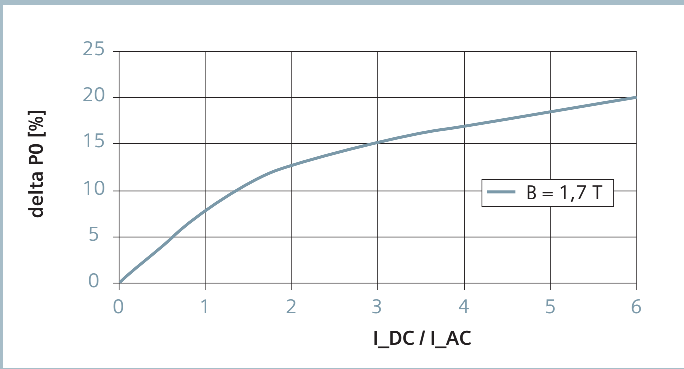

Fig. 3: Increase of noise level under small DC-currents.

Fig. 2 shows the no load loss increase in percent over DC-current based on the AC no load current for a typical core induction of 1.7 T. After a non-linear increase for small DC-currents (here up to $I_{DC} / I_{AC} \approx 3$) the no load losses grow proportionally for higher DC-currents. Fig. 3 shows the noise level increase referring to Fig. 2. The curve apparently has a saturation characteristic. Furthermore it should be noticed that even small DC-currents lead to considerable noise increase.

Additional losses by slight voltage harmonics are a well-known phenomenon from AC-rectifier-transformers and therefore nothing extraordinary. The no-load loss increase due to that phenomenon is less than 2 %.

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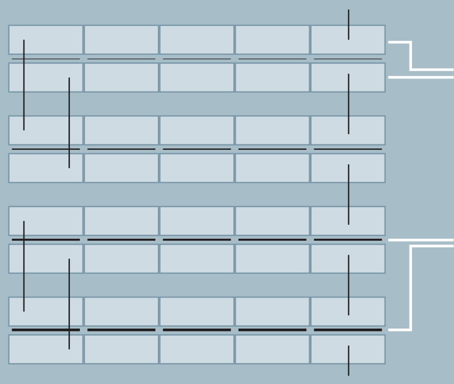

Fig. 4a: Axial interleaved CTC-Winding

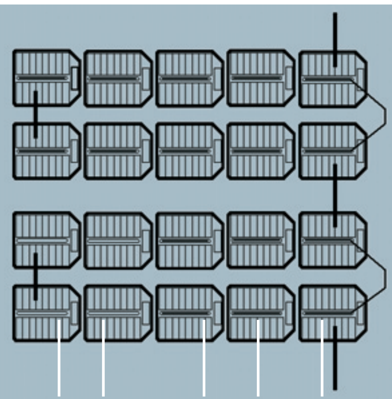

Fig. 4b: Shielded wire inside CTC

3. Windings for HVDC-Design

The AC-winding of HVDC-transformers does not differ from windings of any conventional transformer. The design is made to withstand the stresses in AC-grids. The insulation between AC and valve winding is of course different, since all DC related stresses have to be taken into consideration.

The valve windings, especially the winding at the high voltage end of the rectifier / converter, are something extraordinary. It is usually the wye-connected winding which needs extra care. The AC nominal voltage of the valve winding for a 500 kV-DC-system is in the range of 200 kV. The test voltages of this winding, however, are related to the protection level of 500 kV-DC, which needs significant higher test voltages than for 200 kV AC. The valve winding is either impulse-tested on each terminal (with the other terminal grounded) or on the connected leads against ground (potential impulse test).

The voltage distribution inside the winding at a potential impulse test is completely different compared to terminal to ground stress.

Furthermore, the harmonic currents in the valve winding produce additional losses. Therefore the copper wires must be chosen very carefully; continuous transposed conductors (CTC) are to be preferred.

Interleaved windings are a typical solution for windings to be stressed by high lightning impulse voltages. A significant disadvantage of this type of winding is the extremely high number of solderings and the use of flat conductors, which are subject to comparatively high additional losses.

Better solutions are designs using either CTCs and a special winding entrance (Fig. 4a) or shielded windings (Fig. 4b). Both solutions are designs patented by Siemens.

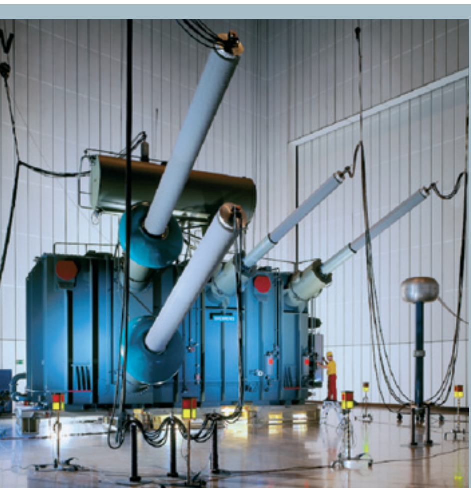

Fig. 5: 397 MVA Yd / Yy single-phase transformer for India with four valve bushings arranged at the long wall of a tank.

Fig. 6: 345 MVA Yd / Yy single-phase transformer for China with four valve bushings arranged at the front side of a tank.

Fig. 7: 283,7 MVA / Yy single phase transformer for China with two valve bushings arranged at the front side of a tank.

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There are only a few or no solderings in the main part of the winding, the manufacturing time is very short and the additional losses by harmonics can be minimized.

Special care has to be taken with regard to the tolerances of all windings. Since the impedance voltage of HVDC-transformers has very small tolerances only, the windings are manufactured and treated with tolerances of +0 / -2 mm in both length and diameter.

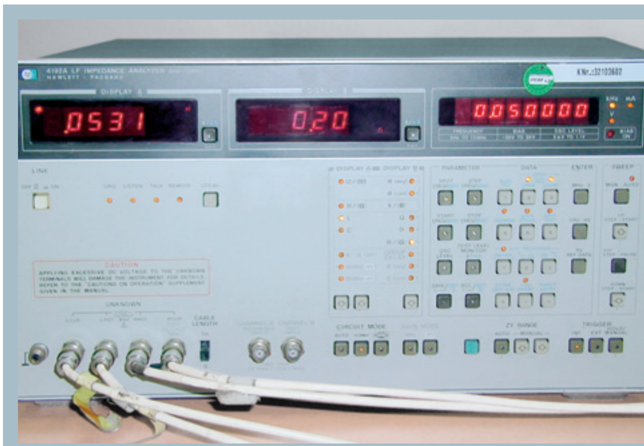

Fig.10: Impedance Analyzer

4. Lead Exits (Valve Windings)

The terminals of the windings must be connected to the bushings. Depending on the type of transformer and its position towards the valve hall, there are different designs (Fig. 5, 6, and 7).

For the designer, the geometrical shape of lead exits is always different. The insulation of the copper tube is made of transformer board in barrier design (Fig. 8). The winding end of the lead must match the winding end barrier system and the bushing end of the lead must match the oil part of the HVDC-bushing. The arrangement and thickness of transformer-board barriers has to be designed for AC, lightning impulse (LI), switching impulse (SI), as well as DC and DC-polarity reversal.

Since at DC the voltage distribution is determined by the resistivity of the materials (Fig. 9a) while at AC, LI, and SI it is determined by the permittivities (Fig. 9b), many optimizing calculations are indispensable to finally meet all requirements.

By the way, the resistivity of the materials depends upon field strength and temperature, however different at different materials.

5. DC-Bushings

The requirements of modern DC-bushings are as follows:

- fulfill all requirements of IEC 62199
- no oil filling of bushing parts inside the valve hall
- extremely high creepage distances on the air side, in particular for open-air-bushings

A modern design consists of:

- resin impregnated condenser bushing core
- enclosure of glass fiber impregnated plastic tube
- tube filled with SF_6 (a few bar pressure)
- tube coated with silicon screens

The length of such a bushing can be up to 9.5 m. The creepage length can be up to approx. 24 m.

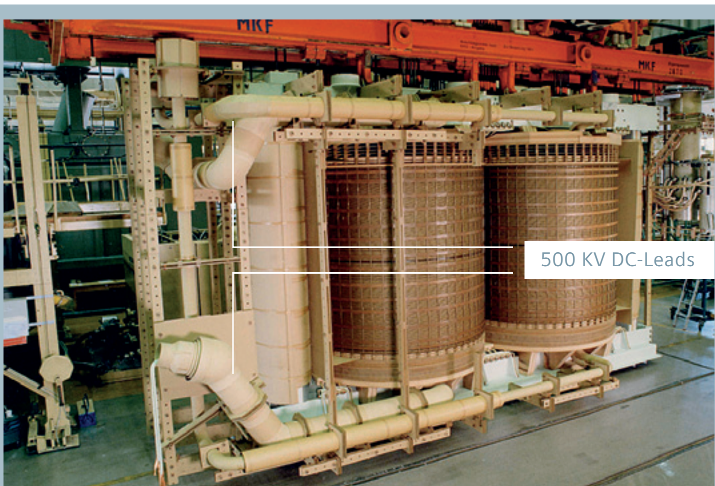

Fig. 8: DC-lead arrangement of a 345 MVA Yd / Yy single phase transformer.

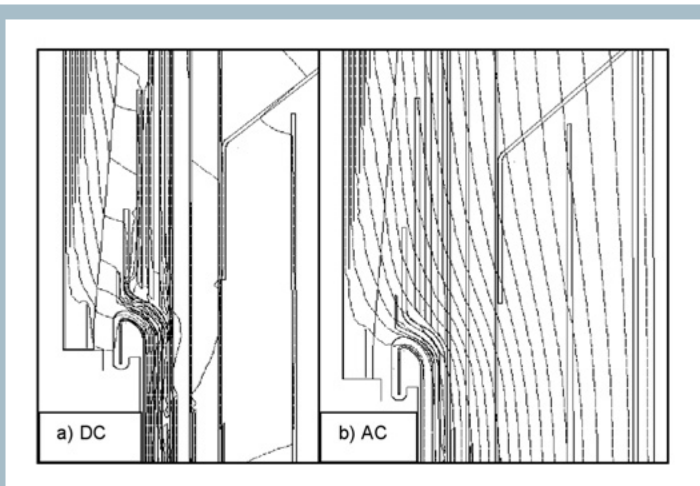

Fig. 9: Field distribution at the oil part of the valve bushing for DC (a) and AC (b) stress.

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6. Testing of HVDC-Transformers

The factory testing of HVDC-transformers is always based on customer specification. The specification itself is based on IEC 61378-2 and / or IEEE C57.129 and may include additional requirements defined by the customer's experts. The testing field itself must be equipped with suitable AC- and impulse generators and with a DC-source which is able to change polarity within approx. 60 seconds. In order to be able to measure partial discharges, the testing field should be properly screened.

Factory tests are usually quite time consuming. Therefore, tests, which from a technical point of view are not necessary at each unit, for example, heat run tests, 12-hours-no-load-tests, measurements of electrostatic charging etc. as routine tests should be abandoned.

A special case is the determination of losses caused by harmonics. The aforementioned standards allow different methods to determine the harmonic losses. Comparisons of these methods on several different transformers show that the measurement of the resistance at the single frequencies according to IEEE delivers more accurate results than the two-frequency method proposed by IEC. The total time to measure harmonic factors can be reduced to approximately one to two hours by the use of a digital Impedance Analyzer (Fig. 10) for the measurements.

7. Influence of Used Materials

The materials used in HVDC-transformers are the same as in "normal" transformers. However, it is necessary to consider material properties stronger than in "normal" AC-transformers. Especially the conductivity values of the insulation are important for the design of HVDC-transformers as described above. Moreover, the availability and usability of traditional materials has been changed during the last years, and new suppliers and materials are on the market. Furthermore, the material properties may change due to new requirements like, for example, the new standard for insulation oil. Especially for a sound design of the valve bushing bottom electrodes, the exact knowledge of the material properties of oil pressboard and resin-paper compound of the lower bushing end is necessary. Therefore, Siemens together with German universities and leading component manufacturers investigated various material properties [6].

Fig. 11 shows the conductivity in p.u. for several solid materials, measured at room temperature and at different field strengths.

8. Manufacturing Features

There are some preconditions for the production of HVDC-transformers, which modern transformer factories usually meet:

- high cleanliness of workshop floors
- modern winding machines, able to deal with narrow tolerances
- modern core cutting machines (small burrs, dust free)
- modern vapor phase and vacuum-plant
- proper oil processing equipment
- dust-free handling machinery (cranes!)
- dust free tank supply
- excellent material supplier and dust free material storage
- high quality of maintenance of equipment
- skilled workforce to handle narrow tolerances in all steps of manufacturing.

Besides these general requirements valid for all EHV (Extra High Voltage) transformer production, some of the above mentioned items are of additional relevance for HVDC-transformers. Due to the continuously occurring DC-stress during service or the rather long time of DC-tests and polarity reversal tests, particles must be reduced as much as possible. Abrasion, which normally occurs during the assembly of insulation parts, must be removed at all manu-

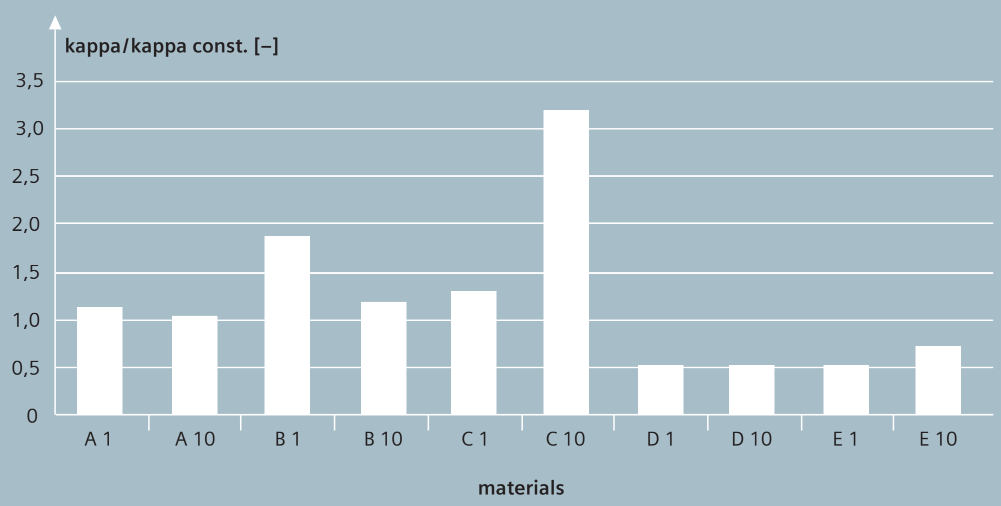

Fig.11: Conductivity p.u. for solid materials:

A. paper
B. paper with adhesion
C. crepe paper
D. pressboard TIII
E. pressboard TIV

1. E=1kV/mm
10. E=10kV/mm

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facturing stages. Even if this is carefully done, some particles will remain and must be filtered from the oil after filling. The manufacturer must define a permissible maximum value for particles in oil. A proper oil treatment plant, which has to be equipped with a reliable particle counting device, is necessary to reduce the amount of particles below this limit. Again, well-trained staff and appropriate equipment is necessary to manage these special requirements.

9. On-Site-Repair of an HVDC-Transformer

HVDC-transformers are subject not only to AC- but also to DC-stress. Therefore, extra care has to be taken during design and also during the production of HVDC-transformers. The same goes – if necessary – for a repair on site.

In summer 2004, one of the converter transformers at TSQ Station (Tianshengqiao-Guangzhou 500 kV DC Transmission) showed an impermissible high amount of gas and therefore had to be taken out of operation. An investigation on site revealed a defect within the line winding of limb No. 2. The customer insisted on the fastest possible way of repair, for which reason it was decided to manufacture a complete winding block at the Siemens factory Nuremberg, send it to TSQ Station and exchange the defect winding block against the new one on site.

In order to have the repaired transformer available during peak season in summer 2005, the whole project had to be finished within 8 months, thus creating enormous time pressure. Siemens established a detailed repair plan. Two major tasks had to be mastered:

- providing a proper environment for the repair on site
- getting all necessary tools / equipment on site in time.

In order to provide the clean environment required, a repair hall was erected by the customer at TSQ (see Fig. 12). It was equipped with air-condition and a removable roof. In mid-February 2005, the hall was finished and the new winding block on its way to TSQ, so the dismantling works of the transformer could start on site. The oil was drained and the tank cover was dismounted. Proper workmanship was particularly required while stacking out the upper yoke and cutting and securing the leads. The winding blocks were exchanged in mid-March (see Fig. 13).

In the following, the leads were reconnected and the upper yoke restacked. Since the active part could not be treated in an oven, it underwent an oil spray drying process inside the transfomer tank with the aid of an oil spray drying device delivered by Siemens. Upon completion, the winding blocks were pressed and the transformer was finally mounted. The transformer was ready for use at the beginning of June, after less than four months of on-site work and just in time before the start of the peak summer season.

Fig. 12: Repair hall at TSQ Station (with the roof re-moving, so the tank containing the new winding block can be lifted into the hall).

Fig. 13: "Old" winding block being taken out of the dismantled transformer with the help of a truck crane (the new winding block is waiting on the left hand side).

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