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800 kV Ultra HVDC Transformer

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SUMMARY

In various global regions there is need to transport maximum quantities of energy, efficiently and cost-effectively over long distances, to meet the constantly growing demand of energy. To master this technical challenge, a transmission voltage level of 800 kV was chosen for UHVDC. To set up the transmitting and receiving stations of such transmission links, UHVDC transformers are needed that feed the corresponding rectifier bridges.

The development of such transformers for the new 800 kV UHVDC voltage range represents a particular challenge.

The design and production of HVDC transformers differ from those of conventional transformers in terms of certain details, and therefore pose a special challenge for manufacturers. In particular, the insulation not only has to be dimensioned for AC stress, but also for DC stress and polarity reversal. This applies especially if this has to be done for a new voltage level that has not been put into operation yet.

In combination with the required transport dimensions, the greater insulation distances call in some cases for distribution of the power to three limbs of a single-phase transformer.

For testing some special requirements have to be fulfilled. Additionally there are some special tests and very high levels of test voltage on valve side.

KEYWORDS

800kV HVDC Transformer, UHVDC, High Voltage DC Transmission, Bulk Power Transmission

1 INTRODUCTION

The first transmission link to submit electrical energy was a DC transmission line between Miesbach and Munich (Germany). In 1882 these line was built by Oscar von Miller using a telegraph cable to submit nearly 1.1 kW of a voltage of 1400 V over a distance of 50 km (Fig 1). At this time conversion of reasonable consumer voltage and higher DC transmission voltages could be only realized by means of rotating DC machines.

In contrast to that, the AC voltage conversion is a relatively simple physical procedure. In addition a three phase synchronous generator is superior compared to a DC generator in nearly every respect. Therefore, the AC technology developed the status of a feasible technology for generation, transmission and distribution of electrical energy in an early stage in the development of electrical power.

However, the AC transmission technology also has disadvantages, for example the limited transmission distance because of inductive and capacitive elements of the overhead

lines and cables. Also the direct coupling of two AC systems with non uniform frequency is not possible. Because of points like that engineers were engaged to develop the DC transmission systems.



Fig 1: "First DC link"

A big milestone was the development of mercury arc rectifiers in the nineteen-thirties. Since this time a commercial and an effective DC transmission of electrical power was possible.

Today the global increase of civilization affects the need for more energy. Often the primary source of energy is far away from civilization and infrastructure. So the electrical power has to be transmitted over large distances.

To master transmission distances of more than 600 km by a maximum quantity of energy in an efficient and cost-effective way HVDC (up to 500 kV) and especially UHVDC (up to 800 kV) is the only feasible transmission technology. HVDC systems up to 500 kV are built in a successful way since the early 1970th. The step up from 500 kV HVDC up to 800 kV UHVDC was necessary to master the big transmission quantities of energy. The 800 kV UHVDC system cuts the transmission costs by about 25 % in comparison to common technology of 500 kV DC systems.

To set up the transmitting and receiving stations of such transmission links, HVDC transformers are needed that feed the corresponding rectifier bridges. The development of such transformers for the new 800 kV UHVDC voltage range represents a particular challenge.

In the development of 800 kV transformer technologies, new solutions were devised in several fields (for example in design and production) that, to some extent, differ substantially from previous known solutions. Some of these special characteristics are explained below with reference to examples.

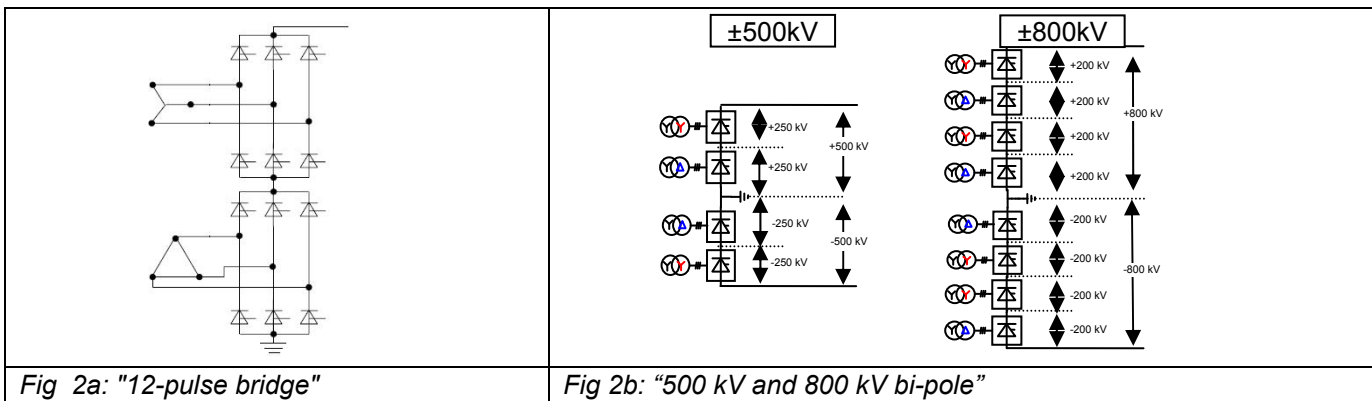
2 HVDC SYSTEMS AND TRANSFORMER REQUIREMENTS

Mostly the HVDC and UHVDC transmission lines are bipolar systems. Each pole consists of two 12-pulse rectifier bridges. Therefore two 6-pulse rectifiers are connected in series (Fig. 2a) by a star delta configuration. Due to the high transmission power mostly single phase transformers are used. In fact of this every phase of such a 6-pulse is feed by one single phase transformer. The three transformers which feed the lower voltage bridge have to be connected in delta configuration on the valve side; the other three transformers for the upper voltage bridge have to be connected in star configuration on the valve side. While two six-pulse bridges result in the full transmission voltage for one pole in the numerous 500 kV systems, four series-connected bridges are used for 800 kV HVDC systems, each of which generates 200 kV DC (Fig. 2b).

Due to the arrangement of the transformers in the rectifier circuit of the bridges there is a need for differing insulation levels, which in this case lead to transformers for the 800 kV, 600 kV, 400 kV and 200 kV DC voltage levels.

The transformers for such HVDC and UHVDC transmission systems have to fulfill some special requirements in comparison to normal AC transformers:

- DC Bias which influences the operation point of the core
- Harmonic Currents which influences the losses
- Combined dielectric stresses of AC and DC voltages
- Special bushing for valve side
- Extra high test voltages at valve winding



The development of the 800 kV UHVDC transformer calls for some more special requirements. The most important restrictions are the transport dimensions and the weight restrictions to ensure the railway transport. In combination with a high rated power and very high test voltages the design process became very complex and challenging. At the same time, the proven design criteria regarding dielectric stresses of 500 kV HVDC systems had to be applied on the insulation systems of 800 kV HVDC transformers.

The transformer for the first 800 kV UHVDC transmission project in the world developed by Siemens with these boundary conditions therefore has the following special characteristics:

- Single-phase transformer with five-limb core, i.e. three wound limbs and two unwound return limbs.
- Connection of the valve windings by an external link that can be dismantled for transport.
- Cooling system on the transformer cover.

3 UHVDC TRANSFORMER DESIGN

3.1 Core

State of the art technology for HVDC transformer is the single phase 2 wounded limb core with two return limbs. As already mentioned, in case of high rated power in evaluation with transportation restrictions it is necessary to split the power within the transformer over three limbs (Fig. 3). Therefore, the windings of each limb are electrically connected in parallel. This is a new solution for a single-phase transformer in this order of magnitude.

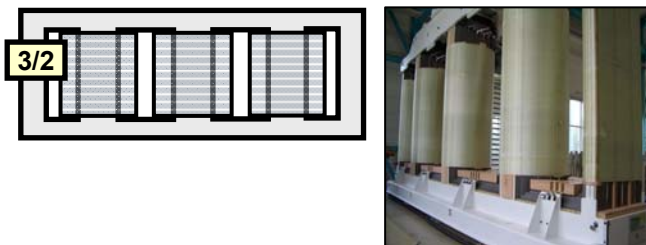


Fig 3: "Core with three wound limbs and two return limbs"

The three limbs' cross-sections are identical, and the cross-sections of the yokes and of the two return limbs each amount to 50 % of the limb cross-section, as it is typical for single-phase transformers with return limbs. Thus, the core is

geometrically similar to the normal five-limb three-phase core. However, the flux distributions with regard to location and time are completely different.

Accordingly, extensive magnetic simulations were carried out in advance to determine the no-load losses, no-load currents and noise development. The simulation models were proven by measurements on five-limb three-phase transformers with similar dimensions. Thus, induction loops had been installed to determine the flux distribution.

As already mentioned, in the design of HVDC transformers asymmetrical magnetic modulation have to be taken into consideration which is the result of DC components in the individual windings. These DC components are caused by operation of the rectifier system. Asymmetrical magnetic modulation leads to increase of no-load currents and losses. This has to be considered e.g. in the thermal design of the core. During operation, these DC components also produce increased noise and vibrations.

In the first 800 kV UHVDC transformer of Siemens domain-refined magnetic steel sheets are used. With a total length of over 10.5 m, the core has been the longest core ever produced at the factory in Nuremberg up to now.

3.2 Winding arrangement, insulation system and valve lead arrangement

The winding design of HVDC transformer in comparison to a conventional AC transformer is basically the same. Therefore, also for the 800 kV UHVDC transformer state of the art winding technology is used.

Corresponding to the insulation levels, the windings were arranged in the order of tapped winding, high voltage line winding, and valve winding, starting from the core. The order is also due to the outer high voltage connection of the valve windings. The winding arrangement in HVDC transformers up to 500 kV is in the order of valve winding, high voltage winding and tapped winding.

For this 800 kV the tapped winding is an interleaved multi-start layer winding. The primary voltage winding is a coil winding type with an axial interleaved entrance area. The valve winding is also a coil winding, where capacitive control of voltage distribution is achieved by field control conductors which are located in the middle of the twin CTC [1]. The winding types chosen allow the use of CTC conductors in all windings. In these

conductors lower losses are produced in comparison flat conductor windings, especially at the windings' ends. In the thermal design, the harmonic currents arising during rectifier operation had to be taken into account. These currents cause a loss increase of 20 % to 40 % in comparison with pure operation with a sinusoidal load current [2].

A specific requirement for the design of the winding insulation arrangement is the combination of dielectric DC and AC stresses.

During operation the valve side of the transformer is stressed by an average DC voltage of $(Z - 0.5)U_{DC}$ with Z being the number of the rectifier bridge. In addition, to the DC voltage an AC voltage of a much smaller magnitude is superimposed. Due to this the valve winding is stressed in operation by a combination of DC and AC voltage (Fig. 4).

In test field the transformer is tested with high DC voltage and separately with very high values of AC voltage. So the design of the insulation arrangement has to be designed for all these cases.

The design for AC stresses is a common one. The AC design criteria have been checked and verified by a large number of conventional transformers with high insulation test levels.

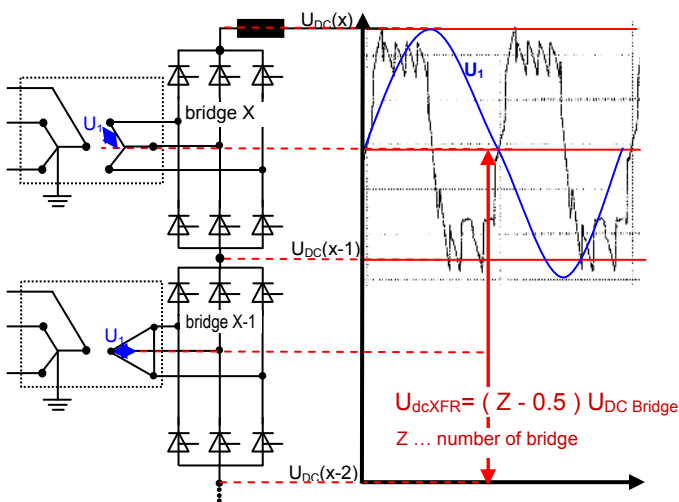


Fig. 4: "operation stresses of a 6-puls bridge"

In contrast the design process for DC stress becomes very important. The design criteria had been checked and verified for the insulation levels of the 500 kV HVDC transformers. For the development of 800 kV insulation arrangements the design criteria of 500 kV had to be checked again very exactly and then it had to be extrapolated up to 800 kV DC. Therefore, special tests and investigations of material properties had to

be done to ensure the safe operation of the insulation systems in the case of acceptance test and field operation. Simulation, design and analysis of highly stressed DC insulation systems require good knowledge of material properties in a wide range of stress duration, including impulse, AC, transient and DC. Standard measurements of permittivity and conductivity are not sufficient for the design of HVDC insulation systems.

Basically there is a big difference between AC and DC dielectric stresses. In the case of AC stress the relevant material parameter is the permittivity. This parameter is well known for each insulation material used. As well the permittivity is constant for nearly the whole range of different boundary conditions like electrical field strength or temperature during acceptance test and field operation.

The determining parameter for DC stress and its calculation is the conductivity of each insulation material used. This material parameter is not known very well and it depends on the operation conditions of transformer. The conductivity depends on the material itself, temperature, stress level and time.

The main field stress during a DC operation is inside the solid materials. In contrast to the main field stress during an AC operation is in the fluid insulation material, inside the oil (Fig. 5). Therefore, the design process for HVDC insulation system is very complex. So the width of the oil ducts is defined by the AC stress level, the thickness and contingent of solid insulation material is defined by the DC stress level. Creepage distances have to be checked and designed for both kinds of stresses.

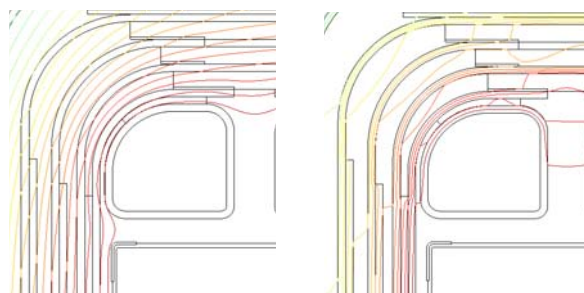


Fig. 5: "Potential field distribution for AC (left) and DC (right) operation "

Valve leads are used to link the three parallel-connected valve windings with the valve bushings. The valve leads consist of an insulated shielding tube around which several pressboard barriers are arranged concentrically. Inside this shielding tube there are the current-carrying conductor lines, which connect the individual winding ends to the valve bushings. The aforementioned

inner tube therefore serves only as an electrical shield which is at high-voltage potential.

The barrier system consists of shaped pressboard parts that are fixed concentrically to one another by spacers.

In consideration of technical issues the combination of the barrier system and the valve bushing is the most sophisticated element of a HVDC transformer [4] [5]. This is because of the combination of three different materials in the barrier-bushing-system. The barrier system consists of paper/pressboard material and oil, the bushings add the third component which is resin impregnated paper (RIP).

Each of these three materials has different permittivity and conductivity. The bushing and the associated barrier system has therefore been developed much sooner than the first transformer, in close cooperation between Siemens AG Nuremberg transformer factory and HSP Cologne [2]. The air side of the valve bushing consists of a SF6-filled combined insulator with silicone shields. Extensive prototypes of bushings and barrier systems were manufactured and type tests were conducted. The level of test voltages for the valve bushings are further 10 % to 15 % higher than the values specified for transformer.

The advantage of a dry type RIP bushing is that no oil-filled part protrudes into the valve hall of the rectifier system. Therefore, the fire load is substantially lower, thus considerably boosting overall system safety.

The SF6 pressure in the outer insulating body is monitored continuously during operation.

3.3 Cooling system

In general the type of cooling in HVDC transformers of Siemens Nuremberg is ODAF (O – Oil, D – Directed, A – Air, F – Forced). This kind of cooling system is used for many years in Siemens transformers and it is well approved. The related efficient heat transfer enables relatively high current densities in the windings. This leads to optimized overall use of material. Especially for HVDC and UHVDC transformers this cooling system is recommended because of the high rated power of the valve windings.

The transformer is equipped with a total of four cooling circuits, one of which acts as a reserve or supplementary capacity for overload operation. In comparison with the conventional arrangement of the cooling system in front of the transformer the

design of the 800 kV transformer is much different. Due to the limits of dimensions the oil/air coolers are located on the top of the transformer tank. However, this arrangement has also a significant thermal advantage; the warm air from the transformer boxes is guided directly upwards. Heat accumulation in front of the radiators is not possible.

3.4 Tank design and cooling system

Conventionally the transformer tank is a closed vessel containing the active part submerged in refined mineral oil. The tank cover, the tank base and the cylindrical boxes so called “turrets” for the bushing connections are the main components of the transformer tank. Relating to the specification the cover and the tank include functions for oil filling, draining, oil sampling, internal inspection, handling and transportation.

In comparison to other conventional HVDC transformers the tank design differs especially by the external connection of the three valve windings. Due to this on the valve lead side the transformer tank has six large openings. Also there are two boxes along the tank side which carries the valve lead connection tube and barrier system inside. Each one of these two boxes has a weight of more than 2.5 t. In addition there are two very long bushings on the front of these two boxes. All these elements introduce considerable forces into the tank. These situations were simulated by FEM tools to ensure mechanical stability and to optimize the appropriate mechanical field strength with economic use of material (Fig. 6).

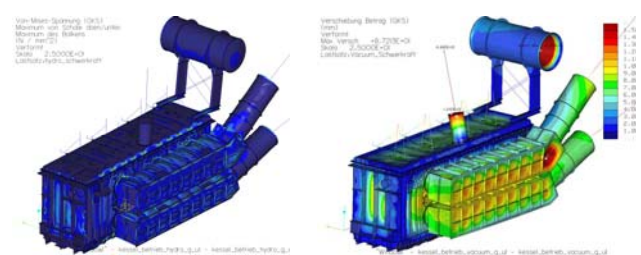


Fig. 6: "tank under operating conditions (left), during the period of time while vacuum is applied on the tank (right)"

3.5 Tests

IEC 60378-2 specifies the tests and test sequences for HVDC and UHVDC transformers. In addition to the IEC specified tests the customer requires some more special tests or different acceptance criteria.

There are type tests, routine tests and special measurements.

Besides the measurements done for every transformer (winding resistance, losses, impedance values, heat development etc.), it is the dielectric tests that pose the special challenge due to the test voltages and times involved (Table 1). To test the dielectric DC withstand capability of the transformer there are two special tests for valve windings: The long term 120 min DC applied voltage test with partial discharge criteria during the last 30 minutes and the polarity reversal test with PD criteria during the whole test run (acc. IEC 61378-2).

The high magnitude of AC applied voltage is to ensure that the transformer will withstand the combined stressed of a high DC voltage superimposed by an AC voltage with a much lower magnitude (Fig. 4).

In particular, the SI switching impulse voltage and the AC voltage levels call for appropriate shielding measures on both the valve bushings and the connections to the test voltage generators, to avoid external flashovers and corona discharges.

Table 1: Comparison of test voltage levels of valve windings of 500 kV and 800 kV HVDC transformers

Voltage Testing	500 kV	800 kV	Change in %
AC long duration (1h)	600 kV	909 kV	+52
DC long duration (2h)	+800 kV	+1254 kV	+57
PR polarity reversal	±580 kV	±969 kV	+67
LI lightning impulse testing	1550 kV	1800 kV	+16
SI switching impulse testing	1300 kV	1600 kV	+23

3.6 Reference and Facts

The worldwide first 800 kV UHVDC transformer passed all test cycles in September 2008 in the Siemens transformer factory Nuremberg (Fig. 7).

Technical data

Rated power: 250 MVA

Vector group: li0

Ratio:

525 kV/ $\sqrt{3}$ +22.5-7.5 %/

168.85 kV/ $\sqrt{3}$

Total weight:

512 t, oil: 142 t

Dimensions:

(26.1 x 15.2 x 6.4)m

Insulation level

Line winding:

LI 1550 kV SI 1175 kV AC 680 kV

Neutral:

LI 185 kV AC 95 kV

Valve winding:

LI 1800 kV SI 1600 kV

AC (1h): 909 kV

DC (2h): + 1254 kV

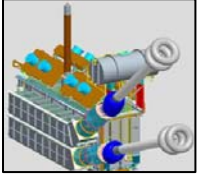
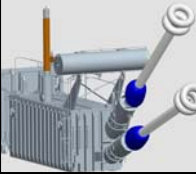
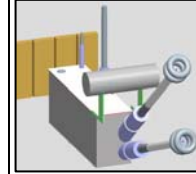

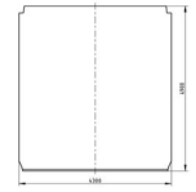
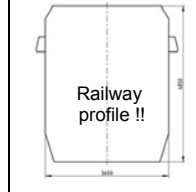
PR (90 min/90 min/45 min): ± 969 kV



Fig. 7: Technical data and picture of the 800 kV HVDC prototype

3.7 Innovations

The first step in the development of 800 kV UHVDC transmission is done, a number of 800 kV and 600 kV transformers are manufactured and well tested. However, the next step of development has to be done. New projects for UHVDC 800 kV transmission are planned, again with an increase of rated transmission power. Due to this, also the rated transmission powers of the transformers increase, although the transport dimensions and requirements are the same. This will be the next most important challenge: increase of rated power, nearly the same test voltages, equal or lower allowable levels of PD and constant transport requirements. Fig. 8 shows the comparison of the “old” and new 800 kV UHVDC transformer prototypes.

		
		
250 MVA / 800 kV	321,1 MVA / 800 kV	360 MVA / 800 kV
Successfully tested	Currently in manufacturing	Study
<i>Fig. 8: Development of UHVDC 800kV transformers</i>		

4 FURTHER REMARKS

The development of transformers for 800 kV HVDC transmission is a milestone in transformer technology.

Product development and production call for close cooperation between all those involved, i.e. the system planners, the transformer manufacturer and the relevant material suppliers.

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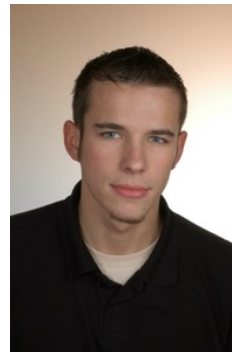
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6 BIOGRAPHIES



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He graduated from Dresden University of Technology in 1997 in High Voltage and High Current Engineering. He holds a Dr. Ing. from TU Dresden (2002) and an Executive MBA from Kellogg-WHU (2006). He started his professional career in a research project with ABB in Zurich and continued in R&D with SGB in Regensburg, where he later became Head of Engineering. He is heading the Engineering Department of Siemens Power Transformers Nuremberg since 2007.



Ronny Fritsche was born in L obau, Germany, on June 12th, 1981.

He graduated from the University of applied sciences in Zittau and received his Dipl.-Ing. in Electrical and High Voltage Engineering in 2006.

He works for Siemens Power Transformers since 2006 as an Engineer responsible for research and development in Nuremberg.