DEVELOPMENT OF A 1200KV UHVAC TRANSFORMER

Dr. R. Wimmer*, Dr. J. Hoppe, M. Rösner, Dr. M. Schenk
Siemens AG, E T TR EU PN EN, Katzwangerstr. 150, 90461 Nuremberg, Germany
*Email: rene_martin.wimmer@siemens.com

Abstract: The rapidly growing energy demand in India led to the consideration of a UHV transmission line (UHV – **U**ltra **H**igh **V**oltage, 1000 kV – 1500 kV) with a length of approximately 1250 km. In this special case a cost-benefit analysis showed that an AC system in the UHV range is more economical than a DC system. The reason for this is that in this particular project, energy sub-distribution must be possible in several substations along this transmission line. To achieve this requirement, a DC system would need additional inverter stations in each substation, while an AC system does not. In preparation for the project, a test station will be installed in India, in order to collect experience with such high voltages.
This paper describes the development of a 1200 kV / 333 MVA single-phase autotransformer for trial operation. The paper deals with experiences of similar UHVAC transformer and with design aspects which are implemented in the 1200 kV transformer which is currently build in Siemens transformer factory in Nuremberg. It also explains the technical advantages of this design.

1 INTRODUCTION

First concepts for a transmission transformer in UHV range go back to the year 1968. Contrary to expectations at that time, the UHV transmission range did not leave the experimental stage. In the 1990's the existing test lines were removed or transformed to lower voltage levels. Nevertheless the high increase of the need of electrical power leads to a revival of the UHV transmission range both in DC voltage and AC voltage.

2 EXPERIENCE WITH UHV AC TRANSFORMERS IN 1972

After the commissioning of the first 765-kV-System in Canada, experts are thinking about the next voltage step for the operation of transmission systems. It is proposed to employ voltages between 1000 kV and 1500 kV. First thoughts and concepts for a power transformer in UHV AC range started in 1968. For that reason Siemens also developed an UHV-AC-test-transformer for 1200 kV in 1972 (fig. 1 & 2) [1]. The requirements for the first transformer were as follows:
- no regulating winding
- rated Power: 400 MVA
- possibility to cascading
- test Voltages according table 1

Table 1: Test voltages

	High Voltage	Low Voltage	Tertiary
U_m in kV	1200	525	30
AC (1min) (in kV)	1200	680	70
AC (1h) (in kV)	1040	455	-
BIL (in kV)	2400	1550	170
SIL (in kV)	1950	(1175) Design Value	-

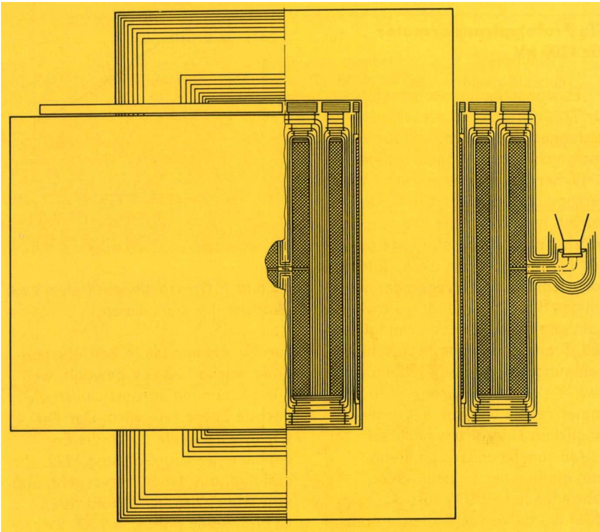

Figure 1: Principle drawing of windings and insulation arrangement of the 1200 kV transformer

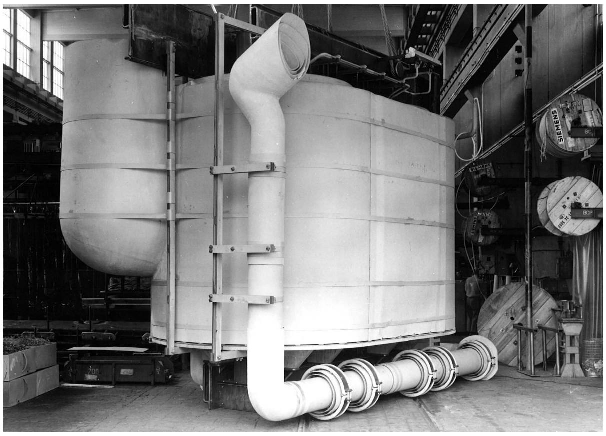

Figure 2: Active part of the 1200 kV prototype transformer

This transformer was designed as an autotransformer with 2 wound limbs without return limbs and centre entry for the HV-winding. The connection between series and common winding was realized underneath a combined static ring. Fig. 1 shows the principle drawing of the active part and fig. 2 shows the active part of the prototype transformer. In 1972 the transformer was successfully tested (fig. 3: the prototype transformer in the test bay). The transportation dimensions were approximately 7.5 m length, 4.7 m width and 5.6 m height.

Figure 3: 1200 kV prototype transformer in the test bay Nuremberg

3 THE UHV AC TRANSFORMER OF 2011

3.1 Requirements

The rapidly growing energy demand in India has led to the consideration of an UHV transmission line (UHV – Ultra High Voltage, 1000kV – 1500kV). A cost-benefit analysis has shown that an AC system in UHV range is more economical for this transmission line than a DC system. The reason is that an energy distribution should be possible in several substations along this transmission line and the AC system does not need additional inverter stations. To get more experience with UHV AC transmission a test station in India will be built. Among other things the transformer has to fulfil the requirements according to table 2 and 3:

Table 2: General requirements

Rated voltage (in kV) (HV / IV / LV):	$\frac{1150}{\sqrt{3}}$ / $\frac{400}{\sqrt{3}}$ / 33
Rated power (in MVA) (HV / IV / LV):	333 / 333 / 111
Voltage variation (based on nominal voltage):	±12.5 % (transformer should operate at nominal power with this voltage variation)
Phases:	Single phase
Impedance at nominal tap:	HV-IV 18 % HV-LV 40 % IV-LV 20 % without reactor
Tap changer:	No tap changer envisaged
Max. PD level	≤ 300pC at $\frac{1.5 \cdot U_m}{\sqrt{3}}$ (ACLD (60 min))

Table 2: The test voltages for this transformer

	System			
	HV	IV	LV	NP
U_N (in kV)	$\frac{1150}{\sqrt{3}} \approx 664$	$\frac{400}{\sqrt{3}} \approx 231$	33	-
U_m (in kV)	1200	420	36	17.5
BIL (in kV)	2250	1300	170*	95
SIL (in kV)	1800	1050 (Design Value)	-	-
ACLD (in kV) (1min)	$\frac{1.7 \cdot U_m}{\sqrt{3}}$ ≈ 1180	-	-	-
ACLD (in kV) (60min)	$\frac{1.5 \cdot U_m}{\sqrt{3}}$ ≈ 1040	-	-	-
$AC_{applied}$ (in kV)	38	38	70	38

3.2 Winding Arrangement

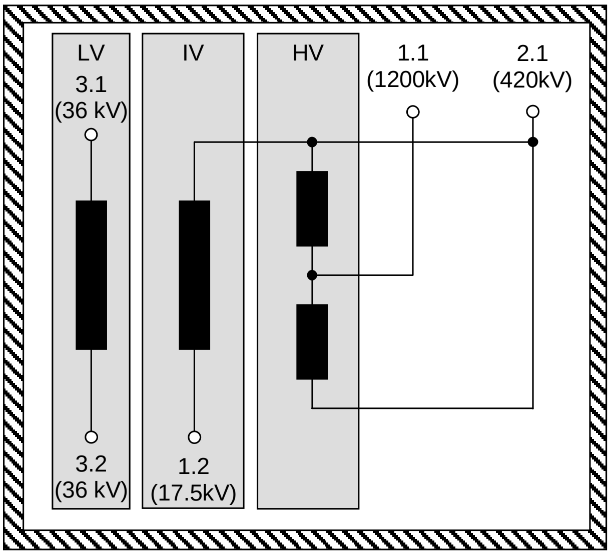

Figure 4: Principle drawing of windings and circuit diagram of the 1200 kV transformer

The configuration of the UHV AC transformer is similar to the prototype manufactured in 1972: The transformer is designed as an autotransformer with 3 winding. The inner winding cylinder is the tertiary winding (LV), the middle winding cylinder is the common winding (IV) and the outer winding cylinder is the serial winding (HV) with centre entry. The circuit diagram is shown in fig. 4. The advantage of the entry is that the voltage of 1200 kV is in the lead exit area of the winding, which has a homogenous field distribution. In that case the insulation arrangement for the 1200 kV parts is much simpler as it would be necessary on the top of the winding. Another advantage is that the 1200 kV exit lead does not need as much space in the transformer as on the top of the winding and can go directly through the tank wall to the bushing (fig. 5).

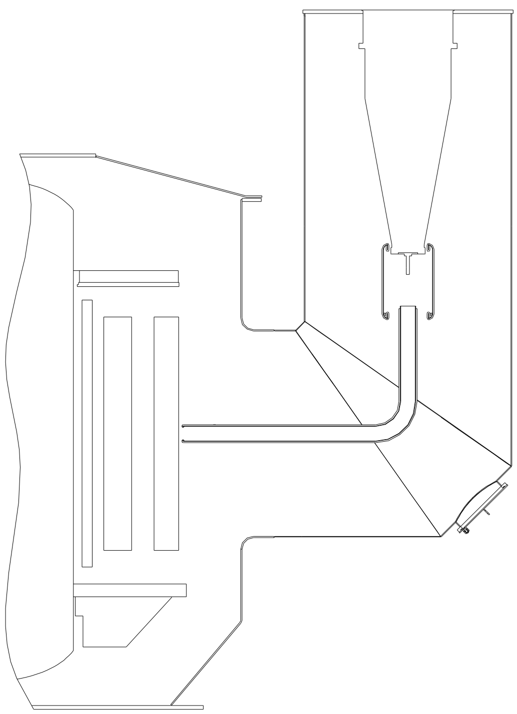

Figure 5: 1200 kV exit lead through the tank wall

3.3 The Volume Effect

Because of the higher voltage and insulation distances UHV-transformers have a larger oil volume compared to normal HV transformers. Therefore the volume effect has to be taken into account for the dimensioning of the insulating system. One possible explanation of the volume effect is the magnification law which is described in the paper from W. Widmann [2]. The oil volume will be divided in a multitude of small volume elements. However each volume element has another voltage withstand because of impurity inclusion like particles or micro bubbles. The voltage withstand of the general arrangement is affected by the poorest volume element. The probability of particularly poor volume elements increases by increasing the whole oil volume. This leads to the fact that the averaged dielectric strength decreases with increasing oil volume. However, this explanation is only a simple consideration of the volume effect. In practice the breakdown of one small volume element does not lead to the breakdown of the whole system if the clearance is beyond a certain value. In this case the breakdown of the small volume element will only be a partial discharge.

It is also described in W. Widmann's paper [2] that the breakdown probability is not only a function of the volume but also a function of time. Due to the movement of the particles or micro bubbles in the oil volume, a bad constellation of the particles or micro bubbles can occur after a certain time.

Another possible explanation of the volume effect is described in the paper of Weber und Endicott [3 - 5]: the degradation of the voltage withstand of large oil volumes is affected rather by the large electrode area than by the stressed oil volume. Here it is assumed that the density of charge carriers is higher near the electrode and the breakdown will be initiated in this area. The cause of the breakdown in this case is the electrode area and not the stressed oil volume.

N. Giao Trinh has made investigations concerning the volume effect [6] with both possible explanations. He concludes that for technical-quality oils both the electrode area and the stressed oil volume affect the voltage withstand of large oil volumes.

Therefore, the normal design curve for dielectric field strength cannot guarantee the same reliability for the 1200 kV transformer as for a 420 kV transformer. The design curve has to be adequately adapted.

In past a new AC design criterion was already developed applied and successfully tested for the 800kV UHVDC transformer. This criterion can be also used for the 1200 kV transformer because the AC test voltage level for the 800kV-HVDC-transformer is similar to the 1200kV-AC-transformer.

3.4 The Half Turn Problem

In some cases it is preferable that the exit leads of a winding are on different core windows. This means: while the entry of the winding is on the high voltage side, the exit of the winding is on the low voltage side (fig. 6). In such case the winding will have a half turn. However the half turn generates an additional flux with a closed magnetic circle via yoke and return limb. This leads to an asymmetric ampere turn in the core (fig. 7).

The consequence of the uncompensated ampere turn is a significant additional flux and increased no load losses. During service the additional flux would cause core saturation which would lead to a heavy overheating of the core. The use of compensating windings which are added on the return limbs can avoid such uncorrected ampere turn [7].

Remark: From the physical point of view a half turn never exists. The turn will always be closed outside of the active part.

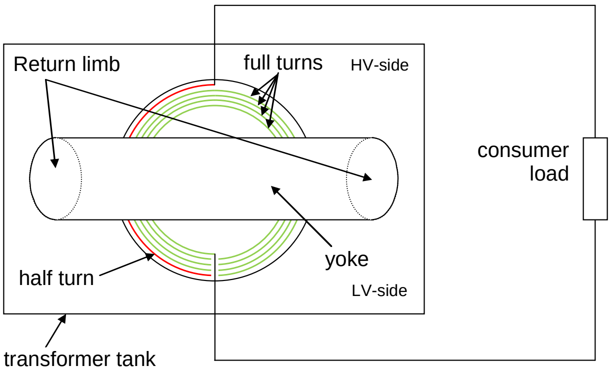

Figure 6: Top view of the active part

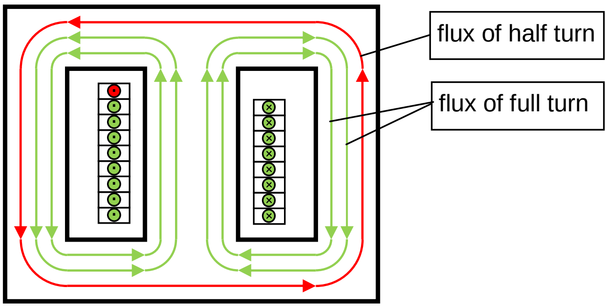

Figure 7: Flux distribution in the core

To avoid half turn problem the exit leads from the parallel and series winding of the 1200kV transformer are on one voltage side. The disadvantage which has to be accepted in such case is that the 420kV lead has to go around the return limb.

3.5 Impulse Voltage Withstand

The high lightning impulse level (BIL) and the centre entry which cuts the effective winding length into half. Therefore, special requirements concerning the withstand voltage along the winding are necessary. Compared to a 420 kV transformer with a BIL-level of 1550 kV the voltage gradient along the UHV winding is nearly 3 times higher than the 1200 kV winding.

Fig. 8 shows a scheme of a transformer winding. The voltage distribution along such a winding is given by the ratio between coupling capacitance C_s and earth capacitance C_e. The lesser the ration C_s/C_e the stronger the initial distribution deviates from the final distribution (fig. 9). This deviation leads to stronger transient oscillations and so to higher insulation stress of the winding during the transition from the initial distribution to the final distribution. The most common method to control the voltage distribution is to increase the series capacitance C_s. This can be achieved with interleaved windings as it is shown in fig. 10. In the 1200kV transformer a fully interlaced winding is used. The additional decrease of the voltage gradient due to interleaving leads to a very good impulse voltage distribution along the winding.

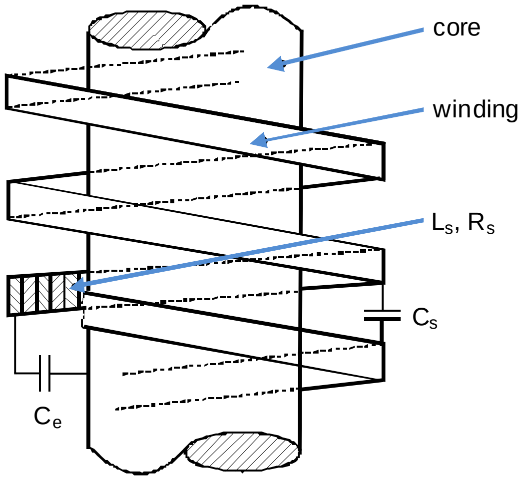

Figure 8: Scheme of a transformer winding with C_s = series capacitance, C_e = earth capacitance, L_s = series inductance and R_s = series resistor

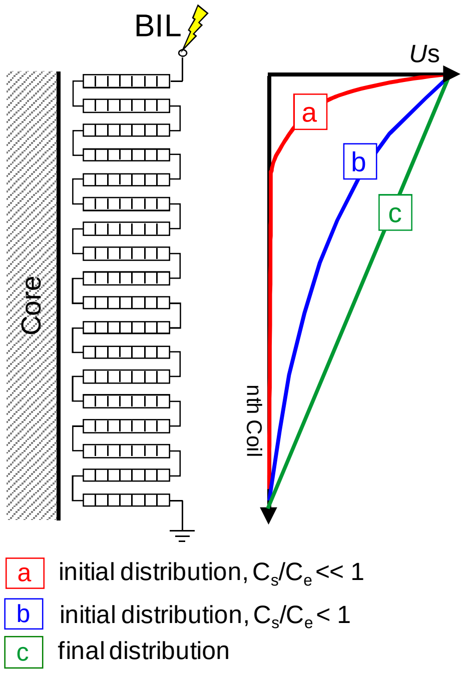

Figure 9: Impulse voltage distribution along the winding

Remark: Another method would be the decrease of the earth capacitance C_e by using an electrostatic shield connected on the high voltage entrance. But this requires the increase of stray ducts and is for that reason not practical in our case.

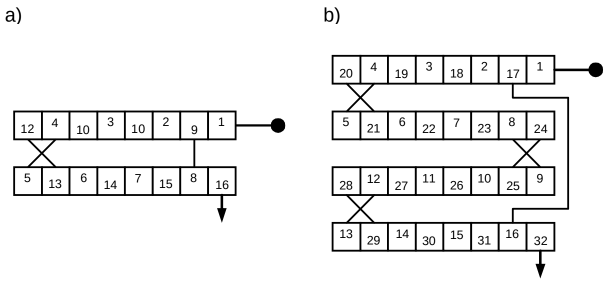

Figure 10: example for interleaved winding
a) over 2 discs
b) over 4 discs

The 1200 kV entrance area of the series winding should also be carefully regarded because of the 1200 kV lead exit tube. During the lightning impulse the voltage drops down along the winding while the voltage of the tube of the 1200 kV exit lead remains constant. However the tube covers several discs of the UHV winding and a high potential difference can be generated between winding and tube. For that reason it is necessary that beside the insulation technique a certain distance between tube and winding is guaranteed.

Such high requirements are not given for the common winding:

1. The BIL-level of 1300 kV is much lower than for the series winding
2. The whole axial length is available for the voltage drop.

Therefore a disc winding without radial ducts can be used as the common winding. The 420kV exit lead is on the top of the winding and neutral point is on the bottom of the winding.

3.6 Further Design Aspects

The UHV-AC-transformer has no regulation winding. This means that the voltage regulation has to be accomplished by an additional transformer, connected on the 420 kV side. This leads to the fact, that the UHV AC transformer has a voltage variation of ±12.5 % based on its nominal voltage. The requirements envisage that the transformer is able to work on every voltage with the nominal power. Hence it has to be taken into consideration that the current of the UHV AC transformer can be 12.5 % higher which affects cooling and winding design.

The critical test voltage for the stress in oil is the AC long duration (ACLD) test. Nevertheless, the layout of the insulation for the UHV AC transformer is basically conventional. This means it consists of the usually used oil-pressboard barrier system and paper insulation. In contrast to the disproportional rise of the necessary insulation clearance of air, for oil it is possible to achieve a linear behaviour between voltage and distance with the right arrangement of the barrier system. Fig. 11 shows a top view of the transformer with the electrical field distribution in oil at 1.5*Um/√3.

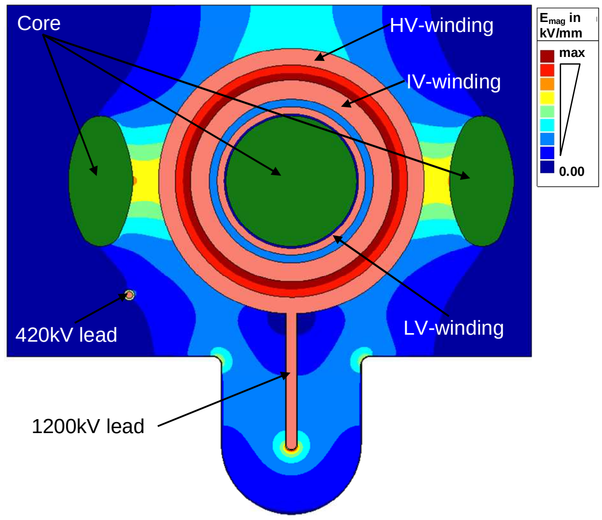

Figure 11: Top view picture of the electrical field strength in oil at 1.5*Um/√3

In the UHV range the switching impulse (SIL) does not have such a high importance for the inner insulation like for the dimensioning of clearances in air. Even in strongly inhomogeneous electrical fields the insulation arrangement is not endangered by SIL.

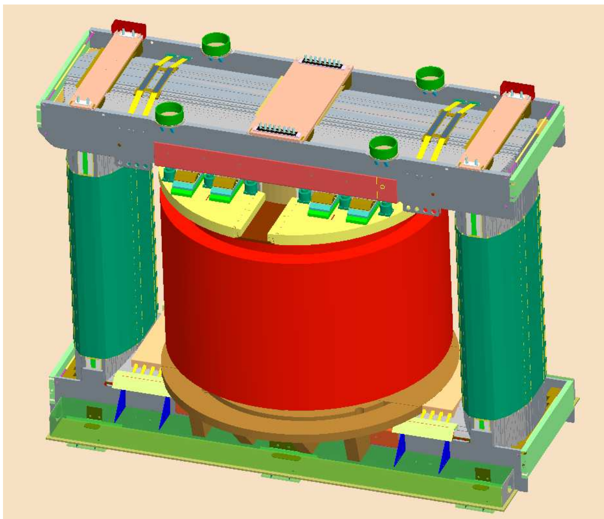

Figure 12: Perspective picture of the active part

The nominal power required by the customer is 333 MVA. This is a power which can be transmitted on one limb. Hence a 1 / 2 core will be used which means one wound limb and two return limbs. This allows a compact design of the transformer. The transport dimension of this transformer is 7.25 m length x 4.7 m width x 4.6 m height. In Picture 12 a 3D drawing of the active part is shown. Picture 13 shows a 3D drawing of the whole transformer.

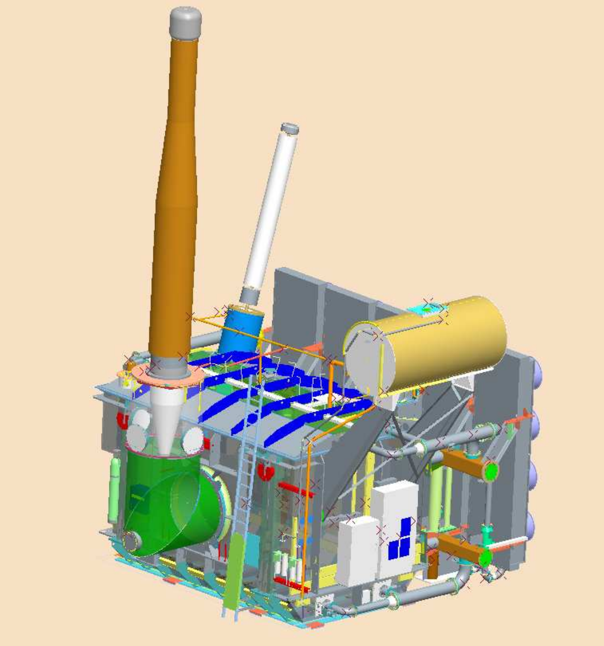

Figure 13: 3D-drawing of the transformer

4 CONCLUSION

Compared to the prototype from 1972 a similar UHV-AC-transformer was designed. The main differences are transport dimensions, profile of the core and the arrangement of the 1200 kV exit lead. An internal design study of Siemens AG proved the manufacturing possibilities of a 1000 MVA / 1200 kV transformer. For this purpose, basically the presented transformer has to be enlarged, using the same concept of winding arrangements. The core of such a 1000 MVA transformer will have 3 wound limbs with 2 return limbs, in order to meet the height limitation of transportation.

5 REFERENCES

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