Testing methods for 1100 kV UHVDC transformer

Thomas Hammer[1], Rene Wimmer[1] , Karsten Loppach[1], Ronny Fritsche[1]
1. Transformers, Siemens Energy, Siemens AG, Nuremberg 90461, Germany

1 Development of UHVDC transmission capabilities

The economical development of China is closely connected with safe and reliable power supply. Load centers e.g. in central and eastern China need huge amounts of electrical power. Available energy resources and consumption areas are often distributed inverse. As a consequence it is necessary to import electrical power to load center areas in an economic and efficient way.

Since many years there are successfully implemented ± 500 kV HVDC connections and UHVAC grids to enable power transmission in the range of 1000 km. For distances up to the range of 2000 km ± 800 kV UHVDC systems are introduced in the power transmission grids.

From some power generation areas with even longer distances to the load centers an even more economic way of power transmission has to be implemented. In 2010 State Grid Corporation of China (SGCC) has decided to introduce ± 1100 kV UHVDC as a new voltage level. This enables connection of electrical power sources and load areas in the range of 3000 km and more.

The Global Energy Interconnection Development and Cooperation Organization (GEIDCO) also addresses UHVDC interconnection to transport electrical power from major renewable resources to load centers. Distances in the range from 2000 km to 5000 km are reported. The implementation of related UHVDC power transmission lines is discussed. Maybe in future also voltage level higher then ± 1100 kV DC have to be considered to ensure economic electrical power transmission.

Received: 2 November 2017/ Accepted: 17 December 2017/ Published: 25 April 2018

Thomas Hammer
thomas.th.hammer@siemens.com
Karsten Loppach
karsten.loppach@siemens.com
Rene Wimmer
rene.wimmer@siemens.com
Ronny Fritsche
ronny.fritsche@siemens.com

2 SGCC UHVDC transmission system "Changji – Guquan" 1100 kV 12 GW

In 2016 Siemens amongst others received the order to supply seven UHVDC converter transformers together with Chinese transformer manufacturers for the 1100 kV DC level for the receiving end of the SGCC "Changji - Guquan" project.

The SGCC project "Changji - Guquan" will carry 12 GW of electrical power from the rectifier station in Changji to the inverter station in Guquan. The overhead line voltage is 1100 kV DC.

At the sending site power will be collected from the 765 kV AC system. On the receiving site power will be transferred to the 1050 kV UHVAC grid and the 550 kV AC grid.

The line commutated converter system is split into 4 DC levels: ±275 kV DC, ± 550 kV DC ± 825 kV DC and ± 1100 kV DC. In each station and in each level 6 HVDC converter transformers carry power to or from the converter, 3 single phase HVDC converter transformers on the positive polarity side and 3 single phase HVDC converter transformers on the negative polarity side. The 7th single phase HVDC converter transformer is used as spare unit.

3 Product development challenges

The new UHVDC voltage level of 1100 kV and power rating of 12 GW also lead to a significantly increased rated voltage level and rated power level for UHVDC converter transformers.

As a consequence dedicated R&D was implemented to identify an adequate product design.

Major efforts were taken to e.g. optimize the insulation system between windings as well as the insulation to ground as a basis to study other operational behavior. Due to the fact that the UHVDC level was increased by 37.5% it was decided to prove R&D results by a physical mockup test.

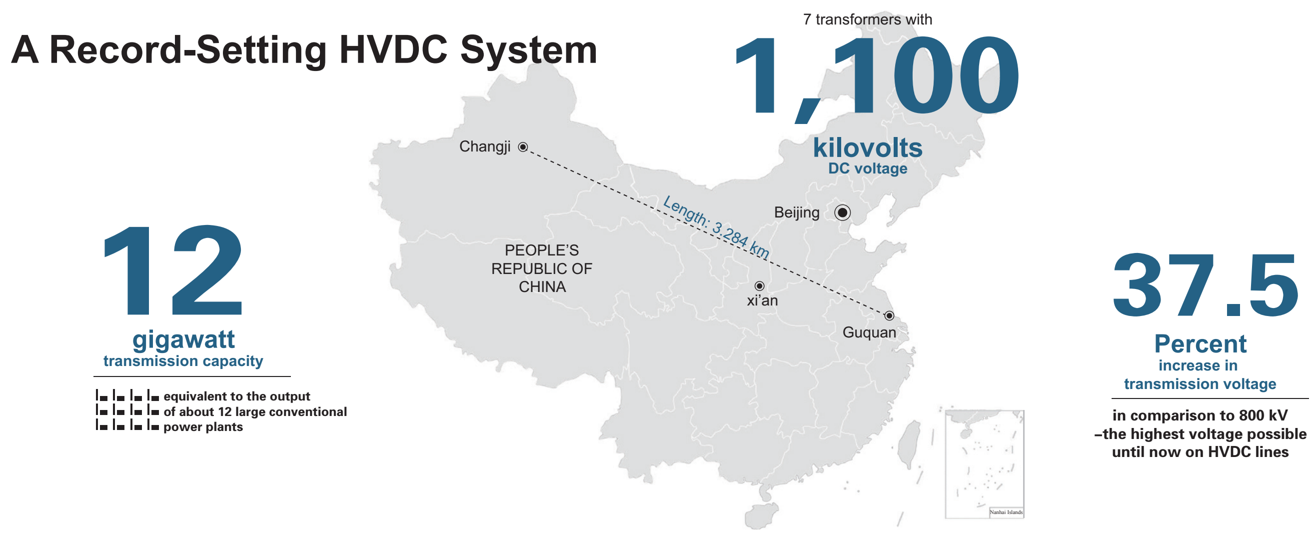

Fig. 1 SGCC UHVDC power transmission “Changji - Guquan”, location

The base map is sourced from SGCC 2017 corporate social responsibility report

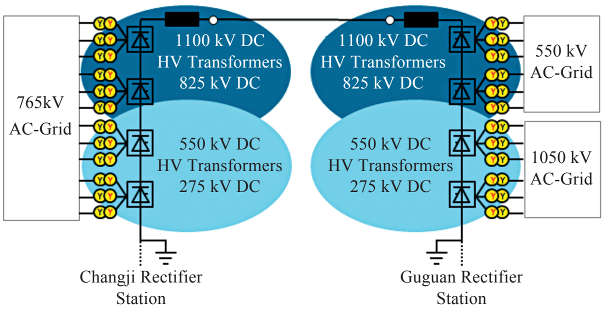

Fig. 2 SGCC UHVDC power transmission “Changji - Guquan”, electrical scheme

In a first step a 10.5 GW transmission was investigated. That means the transformer should have a rated power of 541.5 MVA which corresponds to a rated current of 3878 A for the HY transformer on the valve side. According to these requirements a mockup was developed to check the components like bushing and barrier system.

In this mockup the 1100 kV DC exit lead with barrier systems, the 765 kV AC exit lead with barrier system and the related winding entrance models were assembled. To verify the insulation design the mock up was tested according insulation levels given in Table 1. Furthermore the DC bushing was also tested according to the specified test voltage (see Table 1). In addition to that the AC system replica was tested, too. The voltage levels here for are also given in Table 1.

All tests are carried out according to IEC. In August 2012 the mockup and the bushing successfully passed all tests. Fig. 3 shows the mockup in the test bay.

Table 1 Insulation level of 1100kVDC mockup

Tested system	No	Type of test	Insulation level
DC system transformer level	01	DCapplied (2h) with PD measurement	+1745 kV
	02	PR (90/90/45) with PD measurement	±1354 kV
	03	LI (FW)	–2300kV
	04	SI	–2100kV
	05	ACapplied (60min) with PD measurement	1260 kV
DC system	06		+1995kV
bushing level	07		±1540 kV
AC Um = 765kV system	08	LI (FW)	–1950 kV
	09	SI	–1550 kV
	10	ACLD	785 kV

The mock up test was an important milestone for the development of a real 1100 kV DC transformer. It has

Fig. 3 Prototype test of the 1100 kV bushing at the test bay of the Nuremberg transformer factory

shown that the implemented R&D results work. However, in the mockup only the dielectric needs could be tested.

Other topics like magnetics were still to be discussed and could be only verified on a real transformer.

Additionally in parallel other important topics were investigated: e.g. impact of DC bias in core and clamping design, harmonics and their effects, consequences of increased power rating and optimization of oil directed (OD) cooling inside of windings, size and efficiency of our cooling equipment, stray flux distribution and management inside of the transformer tank and compatibility tests for newly introduced materials.

To study effects 3D simulations were introduced to a significant extent.

In 2014 the 800 kV DC transmission got a new impulse to increase once again the power by increasing the current. The new projects should now have a power transmission of 10 GW at 800 kV DC voltage transmission. For that reason the transmission power of the 1100 kV DC transformer was increased up to 12GW.This increase has had a great impact on the design of the 1100 kV DC transformer and also on the bushing.

As a result of the higher current the temperature rise within the bushing needed to be reconsidered and led to an increase of the diameter of the current carrying copper bar. An increased diameter of the copper bar would result in a larger weight. So the mechanical strength of the bushing also needed to be reconsidered. At the end the increased current led to a new bushing development.

4 Transformer requirements

Final specification was released in 2016. The following tables are an excerpt of the transformer specification and are valid for the 1100 kV DC transformer.

Table 2 Site conditions:

Max. temperature	40.7 °C
Min. temperature	-13.8 ℃
Altitude	<1000m
Average relative humidity	79%
Seismic intensity	6 degree
Dynamic acceleration peak value	0.2g

Table 3 Main parameter 1100kVDC transformer:

	Line side winding	Valve side winding
Rated power	587.1 MVA	587.1 MVA
Rated current (@rated tap position)	1993.8 A	4454 A
Rated voltage	$510kV/\sqrt{3}$	$228.3kV/\sqrt{3}$
Impedance voltage	(22±1.0)%	

Continue

	Line side winding	Valve side winding
Tap range	-5/+25*1.25%	
Grounding type of line side neutral point	direct earthed	
DC bias current	10A	
Type	single-phase two- winding, oil-immersed	

Table 4 Test parameter 1100kVDC transformer:

Kind of test	Duration in min	Terminal line winding in kV		Terminal valve winding in kV	
		1.1	1.2	2.1	2.2
U_m		550	52	1100kV DC-Level	
$AC_{applied}$	60	⏚	⏚	1292	
$AC_{applied}$	1	95		⏚	⏚
ACSD	1	680	⏚	305	⏚
ACLD	1	550	⏚	246	⏚
ACLD	60	476	⏚	213	⏚
$SI_{Pot.}$	—	⏚	⏚	2100	
$SI_{ind.}$	—	1175	⏚	399	⏚
$SI_{ind.}$	—	1175	⏚	⏚	399
LI	(FW / CW)	1550/1705	⏚	⏚	⏚
LI	(FW)	⏚	185	⏚	⏚
LI	(FW / CW)	⏚	⏚	2300/2530	⏚
LI	(FW / CW)	⏚	⏚	⏚	2300/2530
$DC_{applied}$	180	⏚	⏚	1786	
PR	120/120/60	⏚	⏚	1384	

Transportation requirements:

Maximum transportation dimensions (L×W×H) (mm): 15500×5500×6500

Maximum transportation weight (t): 600

The above mentioned parameters adumbrate a huge size of the 1100 kV DC transformer. Due to the fact that the low end transformer are connected to a 1050 kV AC grid the size of these transformer are also huge. Handling the manufacturing of all these transformers is not easy and the manufacturing time increases a lot compared to normal AC transformer units. Consequently the manufacturing of the transformer for Guquan is distributed to keep the delivery time short.

5 Design of the 1100 kV transformer

It is obvious that the design of the 1100 kV transformer is very challenging in regard to several topics.

A specialty of HVDC transformers is that the valve winding needs to be tested with voltages that correspond to the connected system voltage. However the voltage between the terminals of the valve winding is low. This leads to a low number of turns of the valve winding, but a high voltage level of the lightning impulse.

A good impulse voltage withstand capability of the valve winding is determined by a good insulation within the winding and a low oscillation behavior of the winding at lightning impulse stress. An optimized conductor design increases the inner impulse capacitance of the winding. Consequently the voltage stresses between the conductors / discs are remarkably reduced and so the paper thickness of the conductor could be held in a normal range to support proper cooling. The optimized design of the conductor also enables the use of small strands. This is important to minimize the losses in the winding which are generated by the stray flux.

20% of the nominal power is stored as reactive power in the stray flux. For that reason the magnetic design and so the reduction of losses becomes very important. The evaluation of the magnetic measures cannot only be done by standard procedures. Many 3D simulations of the active part and tank are necessary to find the right magnetic screening measures to conduct stray flux and to avoid any overheating.

Such simulations are also done for the electrical field. Also here many simulations are necessary to ensure a safe and reliable insulation design of the winding, exit lead, intermediate electrode and bushing electrode.

Another challenge in the design was to ensure appropriate outside arcing distances between bushings and earth. As a consequence also proper mechanical stiffness of the tank was investigated by 3D finite element calculations.

The overall weight and dimensions of the UHVDC converter transformer itself are a challenge in several manufacturing stages. The impact in the individual production steps were investigated carefully and necessary adjustments were tested and introduced, e.g. active part drying and oil filling procedures for 300t of oil.

6 Test results

In November 2017 the type test of the first 1100kV UHVDC converter transformer took place at Siemens power transformer plant in Nuremberg.

The size of the test object, test parameters, necessary test equipment and right positioning inside of the test facility was challenging as well. Finally all type and routine tests were conducted and completed successfully. Fig. 4 shows the transformer in the test bay.

7 Conclusion and outlook

From 2010 to 2017 significant development steps were taken to successfully produce the first 1100 kV UHVDC converter transformer based on experiences with 800 kV UHVDC converter transformer production.

The industrial experiences on the way to deliver all necessary transformers for the SGCC UHVDC project "Changji - Guquan" will contribute to further optimize the product and procedures.

These experiences shall be discussed in the light of adaptation of existing international standards as well.

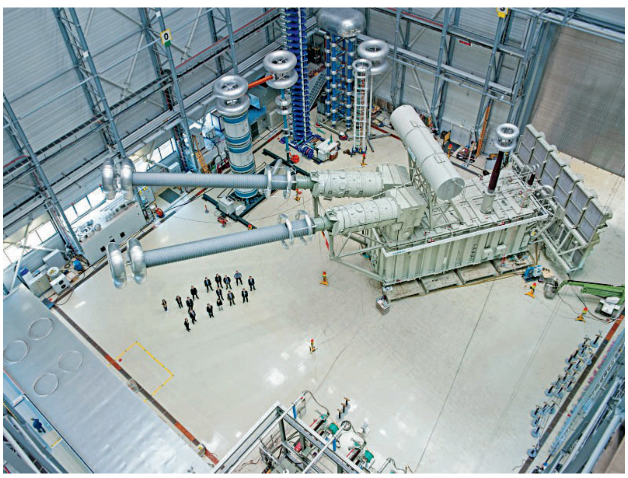

Fig. 4 Prototype test of the 1100 kV bushing at the test bay of the Nuremberg transformer factory

Biographies

Thomas Hammer received his Graduated Engineer in Electrical Engineering 1994 at the University of Dresden, Germany. In 1996 he joined the Siemens AG in Nuremberg, Germany as electrical designer and development engineer for power transformers. From 2005 to 2012 he headed the Department Technology / Innovation for Siemens AG Transformers global. Since 2017 he is director portfolio management Siemens HVDC transformers.

René Wimmer received his Ph.D. in 2010 at the University of Stuttgart, Germany. In 2008 he joined the Siemens AG in Nuremberg, Germany as dielectric design and development engineer for transformers. Since 2013 he is the director of the department of technology transfer for HVDC transformers.

Karsten Loppach is director engineering at the Siemens Transformers power transformer plant in Nuremberg, Germany. After his graduation as an electrical engineer at the Technical University Dresden in 1992, he started his career as an electrical designer at Siemens. He held several positions since then, e.g. as a test bay engineer and head of test bay, as a quality manager and program manager. Since 2010 he is heading the department electrical design in Nuremberg, since 2011 as the director of engineering incl. the responsibility for engineering within the product line HVDC for Siemens Transformers globally.

Ronny Fritsche graduated as an electrical engineer (Dipl.-Ing (FH)) in Germany in 2006. After working as an electrical design engineer for power transformers at the Siemens Transformers plant in Nuremberg for three years, he became an R&D engineer. Sind 2013 he is heading the R&D at the Transformer Factory Nuremberg. Ronny Fritsche is a member of the German VDE and active member of CIGRE (WG A2.59; WG A2/D1.41; WG D.170; WG D1.63).

(Editor Xiangru Chen)