White paper

Developments in UHVDC and UHVAC transmission Power Transformers

Abstract

Long distance transmission by use of HVDC (High Voltage Direct Current) technology is playing a more important role in several transmission systems. With growing transmission power and distance, the need of increased DC-transmission voltage is increasing. At the same time this puts higher requirements on the AC-network to which the HVDC transmission system is connected. Also power transmission by use of UHVAC has spurred increased interest.

The key enabling technology to achieve the interconnection between UHVAC and UHVDC is that of converter transformers, which serves as the link between the AC-network and the DC-converters. This article describes recent developments in converter transformer technology enabling interconnection of UHVAC and UHVDC and provides a description of the state of the technology in this area.

The article concludes that the last years developments in converter transformers has left the state of the art such that any AC network voltage level can be combined with all DC-transmission voltage levels up to and including 1100 kVdc. This should provide optimum flexibility for realizing HVDC systems with any set of parameters.

KEYWORDS, HVDC, ultra-high voltage, interconnection, development, converter transformer

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Introduction to HVDC converter transformers

HVDC converter transformers are thoroughly described in [1]. To briefly recapitulate, HVDC converter transformers are equipment that serve as an integral part of an HVDC system. Their main function is to insulate the DC-voltage of the converter valve from the AC-network to which the HVDC system is connected. All the power that flow through the HVDC system passes the converter transformers, which delivers current on a suitable voltage level to the converter valve, transformed from the AC network voltage level.

As transformers, the converter transformers often become very big in terms of physical size. This partly has to do with the often high power ratings of the converter transformers, but also with the fact that they often are connected to high voltage AC-networks and that the valve winding has high insulation requirements. For this reason dielectric design is in focus for the design of the HVDC converter transformers as both windings in them are having high insulation requirements. The converter transformers not only have to be design for AC-stress, but also for DC-stress generated in tests and in service by the converter valve and DC transmission system. Design for DC-stress have proven to be one of the most complex engineering tasks in the world of transformers. HVDC converter transformers are the most harshly tested transformers in the entire transformer industry. All these together will have a direct impact on the transformer size and therefore, its need to be thoroughly investigated to get optimal solution that cope with insulation and size requirements.

Brief historical background of HVDC and converter transformers

HVDC converter transformer history follow in the footsteps of HVDC system development. As the HVDC converter transformers are most impacted by overall power level, the AC-network voltage level to which the HVDC system is connected and the DC-transmission voltage, the most important historical developments have been connected to steps in these parameters.

The history of HVDC started with the HVDC interconnection to the island of Gotland in the mid-fifties. Neither the power rating of 20 MW nor the transmission voltage of 100 kVdc was especially mind-blowing, but the birth of the overall technology was.

In the following two decades, relatively few transmissions were built and technology emerged slowly. In the seventies, power levels, transmission distances and thereby transmission voltage leap-frogged to a 400-500 kVdc level in projects like CU in USA, Pacific Intertie in USA and Cahora-Bassa between Mozambique and South Africa. This meant that transformer manufacturers where faced with a number of new technical challenges – mainly in the field of dielectrics, since the increase in DC-transmission voltage was directly reflected on the transformer insulation.

Figure 1. 800kVdc converter transformer for the Xiangjiaba-Shanghai 800 kV UHVDC transmission. Type tested in 2008.

The crown jewel from this development phase is the Itaipu in Brazil project supplied by Asea in the beginning of the 1980ies. The project reached an outstanding power transmission level of 3150 MW and a novelty voltage level of 600 kVdc. Nearly all apparatus used for HVDC system were newly developed and in retrospect, the technology developed for this project formed the foundation for all HVDC technology within ABB.

For the coming 25 years, the ratings of the Itaipu project stood unchallenged in the world.

The UHVDC era

China started to build HVDC transmission links in the end of the 1980ies. With the big growth in need of electrical energy, China aimed for large power ratings and high transmission voltages. The first Chinese HVDC transmissions was rated 3000 MW and 500 kVdc – once more the world saw Itaipu-level power transmissions. A spin-off of these HVDC transmissions was the realization that it is possible to have single infeed points in the networks that could handle substantially more than 3000 MW. At the same time, China had access to energy resources with transmission distances to load centers being in the range of 2000 km. The combination of these two parameters led to the investigation of a new voltage level – 800 kVdc or UHVDC. This opened the possibility to investigated higher power transmission rating required by the Chinese electrical energy market.

In the same way as Itaipu was a complete makeover of all technology used in an HVDC system – the development of 800 kV UHVDC meant revisiting all technical areas and that was especially true for HVDC converter transformers. An important part of the development effort was to revive the knowledge from the 1980ies in order to develop completely new transformer technology. The R&D project lasted for a little more than 2 years and ended with full voltage type testing and long-term testing of the newly developed transformer technology. The development process and results have been widely reported [2].

The resulting HVDC delivery project for the first 800 kV UHVDC transmission system to go into commercial operation had a power rating of 6400 MW and a transmission voltage of 800 kVdc. The project, Xiangjiaba-Shanghai has operated successfully since 2010 [3]. It is important to understand that the evolution of UHVDC did not stop with the first Xiangjiaba project. A number of projects at UHVDC voltage level have been executed in China after the Xiangjiaba project, all with increasing power ratings. Increased power ratings of converter transformers leads to increased physical size, while the transport restrictions for transporting converter transformers remain the same. This increase in power ratings have led to a range of novelties in converter transformer design to accommodate physically larger transformers in the same transport restrictions. Between the years 2007 to 2010, the power rating for 800 kV UHVDC projects in China increased from 6400 MW to 8000 MW over a span of 4 projects breaking world records one by one.

The converter transformers have evolved with the increasing power ratings, into more versatile designs with no compromise made on reliability or design margins.

1100 kVdc, 10 000 MW transmission capability for 800 kV UHVDC and interconnection to UHVAC

In 2011, the next major step for HVDC transmission came about when the development of 1100 kV UHVDC started. 1100 kVdc was motivated by being able to transmit very large amount of power of very long distances – 3000 km and more. In order to understand the enormous challenge with 1100 kVdc, we can try to make a test voltage comparison. The 60 minute AC test level of the valve winding for an 1100 kVdc system is 1260 kV. The corresponding AC system voltage level that would have this test level is 1381 kV AC-system voltage. This shows just how big the challenge in insulation is. In the history of HVDC it is also noticeable to see that it only took in the range of 5 years to move from 800 kVdc to 1100 kVdc whereas the step from 600 kVdc to 800 kVdc took 25 years. It should be acknowledged that the percentage

Figure 2. Graph of the power rating and voltage development in HVDC transmission projectss since the first HVDC between Gotland and the main land in Sweden.

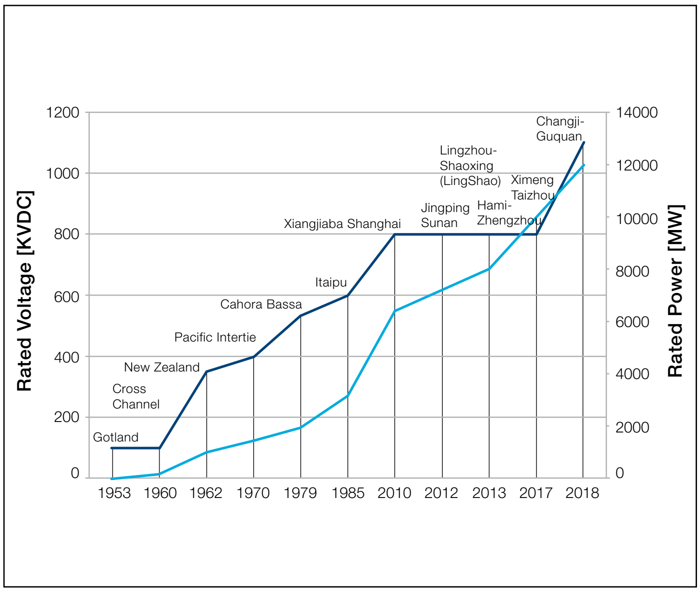

Figure 3. 1100 kVdc converter transformer prototype. Tested up to full test voltage levels in June 2012.

voltage step is bigger between 1100 kVdc and 800 kVdc than the step between 600 kVdc and 800 kVdc.

ABB deployed substantial resources to the development of 1100 kVdc and was the only company to complete the R&D according to the stipulated time plan. Again a completely new transformer technology was developed. Everything was verified with full scale testing using a prototype shown in Figure 3. Commercial application of 1100 kVdc took a little longer than anticipated, by during the year of 2016, ABB has been contracted to supply part of the world's first 1100 kVdc converter transformers.

Two other important developments steps has taken place during the last five years with regards to AC-voltage level and power rating. The first is concerning AC-voltage level of HVDC converter transformers. ABB has developed the ability to interconnect all existing DC-transmission voltage levels to all existing AC network voltage levels by developing the converter transformers further on the AC line side. The first application of the development was for the Lingzhou-Shaoxing project where ABB converter transformers facilitated the interconnection of 750 kVac AC-voltage network with an 8000 MW, 800 kVdc HVDC-transmission. The successful type testing of this technology later led to the contracting of similar technology for the Jiuquan-Hunan project. In the first commercial application of 1100 kV UHVDC-transmission ABB's converter transformers are also connected to a 750 kVac network, further reinforcing the trend of UHVAC to UHVDC interconnection.

The second development step consists of increasing the power rating for 800 kVdc transmission links from 8000 MW to 10 000 MW. To able to increase the power rating with 25%, ABB has developed the ability to handle the increased current for the converter transformer by developing the thermal system as well as handling the additional physical size resulting from the power increase. ABB has been contracted to supply converter transformers for 10 000 MW, 800 kVdc UHVDC-transmission projects.

The power generation in the above projects are located far from load centers and the sending stations for these projects have tough transport restrictions for transporting the converter transformers to site. These transport limitations have been one key issue to handle during the development of the converter transformers. ABB has succeeded to develop these converter transformers with high power and voltage levels within narrow transport profiles. With this proven ABB has the ability to design transformers for remote stations in HVDC projects.

In all the technology steps the last 10 years, ABB has proven the ability to develop technology, prototype it, test it and apply it flawlessly in commercial projects in very short time spans. As a matter of fact, there are approximately as many converter transformers in HVDC projects based on technology developed during the last 10 years as there are in all other HVDC-systems prior to that combined.

State of HVDC system and transformer technology

With the very rapid development of HVDC transformer technology to facilitate power and voltage levels for HVDC systems in the last 10 years, it can be worthwhile to explicitly point out where the state of technology is.

- HVDC transmission voltage. All transmission voltages up to and including 1100 kVdc is available. This includes any voltage between 600 kVdc and 1100 kVdc such as 700 kVdc or 900 kVdc.
- HVDC transmission power. Single 12-pulse groups in bipolar configuration of up to 5000 MW power level can be achieved on 800 kVdc voltage level. For higher voltage levels, even higher power levels might be available.
- HVAC interconnection. Any AC network voltage appearing in the world today can be connected to any DC transmission voltage.
- UHVAC transformer technology. By applying technology developed mainly for 1100 kV UHVDC application, AC-transformer technology for a system voltage of more than 1350 kV is available.

Conclusion

Based on the HVDC converter transformer development mainly for UHVDC a much greater flexibility of HVDC transmissions has been created. Nearly all conceivable rating combinations can be realized. The ultimate conclusion from this is that there is no limitation in what optimization can be made for future HVDC transmissions in terms of DC-transmission voltage or power level or to which AC network the HVDC transmission is connected. This fact makes up for a brilliant future in realizing optimum HVDC-transmissions. There are very few limitations for realizing all conceivable HVDC systems.

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