DESIGN AND TESTING OF 800 kV HVDC EQUIPMENT

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SUMMARY

Bulk Power HVDC transmission schemes over distances of up to 2000 km are currently under planning or construction for various large hydropower stations in India and China. Ultra high dc voltage (UHVDC) at 800 kV is the preferred dc voltage level for these applications. This enables a significant increase of power transfer capability and reduces transmission losses compared to currently world-wide existing HVDC schemes which are limited to maximum voltage levels of 500 kV to 600 kV. However, the impact of increased steady state and transient voltage stresses on the design of the main equipment for UHVDC stations had to be carefully investigated. Adequacy of existing technologies had to be evaluated taking manufacturing capabilities into account.

This paper focuses on specific design aspects for key UHVDC equipment to be taken into consideration. The state of art of HVDC equipment technology and its application in 800 kV HVDC system are described and discussed in detail along with some examples from research and development works.

The results have been considered for the equipment design of the world’s first UHVDC application in China Yunnan-Guangdong which is also briefly introduced.

KEYWORDS

Bulk power transmission, UHVDC, 800 kV HVDC, HVDC Equipment

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INTRODUCTION

The development of HVDC main equipment suitable for operation voltages up to 800 kV dc is based on broad experience with transmission schemes up to 500 kV. Some components of the main equipment do not require detailed investigations since the existing technology basically enables to extrapolate from lower voltage applications. An example for this type of equipment are the thyristor valves which are based on a modular design. Voltage stresses across individual thyristor levels as well as across valve modules are not increased. Only the shielding of the high voltage potential to ground has to be reviewed and modified appropriately. However, for other equipment it has to be verified how far existing technology and know-how is adequate for the design and manufacturing process. This includes the following equipment which will be discussed in more detail in this paper:

- converter transformers including bushings
- dc smoothing reactors
- dc-bypass switches and dc disconnectors

Additional conditions may be important for the design of 800 kV HVDC equipment and must be taken into consideration. The converter stations may be located in areas

- with considerable degree of pollution
- at altitudes of more than 1000 m above sea level
- where transport limitations exist for heavy equipment.

It is worthwhile to mention that the above requirements cannot be regarded as independent of each other. Examples for existing interrelations are:

- The design of leads and barrier systems of the valve side bushings of converter transformers will have a decisive influence on the transport dimensions of the transformers.
- In terms of voltage grading the external insulation of equipment housings must be carefully coordinated with the internal insulation of the equipment in order to avoid excessive radial voltage stresses.
- Mechanical requirements e. g. for post insulators of dc bus bars and disconnect switches result in adverse effects on the performance of external insulation (creepage distance).

It is well understood that mechanical requirements do not only include operational forces but also seismic conditions and wind loads anticipated for the areas where the converter stations will be located. Hence, not only electrical aspects but also mechanical characteristics must be carefully considered for a proper equipment design.

INSULATION CO-ORDINATION

Regarding voltage stresses the design of converter equipment at an increased dc operation level has to consider both steady state as well as transient stresses. Depending on specific characteristics of the individual main equipment, either internal insulation (e.g. paper/oil insulation inside the converter transformers) and/or external insulation design aspects have to be investigated.

In general, in order to fulfill these increased requirements, dimensions of equipment could be enlarged and distances to other components and ground could be increased. However, it has to be considered that in the UHV range some effects can become highly non-linear, i.e. an increase of the operation voltage by 60% (comparing 800 kV to 500 kV) may require to enlarge the distances in air by approx. 100%. Furthermore, manufacturing and transport limitations may impose a “natural” or economical limit for the dimensions of the equipment.
EXTERNAL INSULATION

External insulation includes all distances in atmospheric air as well as surfaces of solid insulation in contact with atmospheric air [1]. While the first is referred to as air clearance between two electrodes which is mainly influenced by atmospheric conditions as air density, the latter is significantly impacted by environmental conditions on site, in particular by pollution and humidity.

Pollution Effects

Pollution on insulator surfaces exposed to dc voltages has been of major concern for several existing HVDC schemes in the past. Different to ac voltages one aspect to be considered is the attraction of pollution particles in the unipolar electric field. Pollution problems leading to surface discharges and finally to a complete insulation breakdown by flashovers have been experienced in a number of HVDC systems. Although these issues have occurred at any system voltage level they tend to be more critical with increasing voltage. It will be therefore crucial to find the optimal solution for applications in the UHV range.

Reviewing experiences of the past decades leads to the conclusion that insulation problems due to pollution occur nearly exclusively on porcelain insulator surfaces. Especially for heavily polluted environmental conditions, accumulated dust settled down on porcelain surfaces can become conductive during light rain or during the dew period in the morning. Furthermore, effects as partial wetting e.g. of horizontally mounted dc wall bushings can lead to breakdown of the insulation. Special requirements on insulator shed profiles and increased creepage distances can improve the insulation performance for specific situations but are still not fully solved and are subject to discussion of experts in international standardization committees. Furthermore, large equipment dimensions resulting from increased creepage distances can lead to difficulties in manufacturing or to transport restrictions.

Several approaches have been applied in the past to overcome the surface insulation problems. Over the past 30 years the use of hydrophobic surfaces significantly improved the performance and reduced the flashover phenomenon dramatically, since the tendency of forming individual water drops on hydrophobic surfaces prevents developing conductive layers. Coating of porcelain insulators, initially by silicone grease and more recently by silicone elastomer was successfully applied. Especially the latter technology was significantly improved through the past years. Both technologies do require the renewal of the material after a certain period, depending on the specific environmental conditions at the site.

A further option for insulators with hydrophobic properties are composite insulators consisting of a glass-fibre tube or core and a silicone housing. Starting with composite dc wall bushings some 30 years ago, drastic improvements could be achieved. The specific creepage distances can even be reduced compared to those of porcelain. In several HVDC projects in China composite insulators with 75% creepage distance compared to porcelain are in operation since several years and show excellent performance.

Over the past years, the application of the composite insulator technology was further extended to other types of converter main equipment such surge arresters and voltage dividers.

It was obvious that the excellent experience gained with this technology favours its application for UHVDC. Furthermore, extending the range of applications to other outdoor equipment exposed to environmental conditions was anticipated. This included mainly the following components: busbar support insulators, dc disconnectors, dc bypass switches and dc plc capacitors. The technical
specifications for outdoor components using composite insulator technology required a minimum specific creepage distance of 40.5 mm/kV based on the rated dc voltage of 816 kV. Creepage distances of large diameter equipment have been corrected according to common practice known for ac applications. Example pictures of equipment designed with composite insulators are shown below.

Figure 2: DC Disconnector in test field (composite insulator technology)

Figure 3: DC bypass switch during wet dielectric test

Air Clearances

As mentioned above, some aspects can become non-linear when entering the UHV range. This is specifically valid for the switching impulses withstand voltages which are decisive for air clearances in this voltage range. As the general aim of insulation coordination is to find an economically and technically optimized arrester protection scheme, for such UHV applications additional arresters can be useful to limit the withstand voltages to values optimizing the equipment regarding manufacturing and transportation. Details on specific aspects of insulation coordination for UHVDC schemes are not discussed here but it is referred to the corresponding literature [2].

Clearance distances in air depend strongly on the electrode shapes under consideration. These result in the so called “gap factors” which are commonly used to determine minimum clearance requirements. For outdoor installations it is crucial to base the component design on pessimistic gap factor as environmental conditions can influence the electrode shapes in practise. As an example, rain drops can lead to more unfavourable shapes of shielding electrodes. It should be noted here, that the procedure of calculation of minimum air clearances is restricted to untested equipment (e.g. busbar arrangements) and to the preliminary design stage of main components. Finally, components can be also designed with smaller distances than calculated if the type tests have been passed successfully. For indoor installations – namely the valve hall building – the influence from environmental conditions can be well controlled and allows reducing air clearances to lower values by designing optimized shielding electrodes. This increases the gap factors and can be useful to limit valve hall dimensions. As an example the valve tower shielding on 800 kV potential is discussed. It presents the lower end of a double valve tower which is suspended from the ceiling of the valve hall.

The minimum air clearance to the floor has been investigated. Toroids with different diameters have been designed and appropriate distances were verified by tests in a high voltage test laboratory in order to determine the critical flashover voltage (CFO) for various distances. Typical examples are
shown in the figures below.

Figure 4: Valve tower shielding replica during dielectric testing

**External insulation of dry type smoothing reactors:**

There are two alternative technologies available for smoothing reactors which have been used for HVDC projects in the past,

a) oil-immersed, and  
b) dry-type.

As extensively discussed within the HVDC community the technology selected for the first UHVDC projects is dry-type, air core. Dry-type air-core reactors are a design family of coils without a magnetic core, with concentric multilayer windings, consisting of epoxy fibreglass encapsulated conductors regularly distributed along the vertical axis of the coil. After curing of the epoxy resin the winding constitutes a rigid, mechanically robust unit which is mounted on a number of support insulators to provide the clearance for the insulation to ground.

There are economical and technical reasons which favour the selection of the dry-type technology for UHVDC smoothing reactors. The most compelling technical argument is the simplicity of the reactor's insulation to ground. HVDC smoothing reactors are connected in series to the converter terminals. When being connected to the pole side terminal, the reactor is on full dc potential with respect to ground. The upgrade from existing dry-type smoothing reactor designs for 500 kV to 800 kV essentially concerns to the insulation to ground whereas there is practically no design change for the winding itself. For an oil immersed reactor however, the raise of voltage to 800 kV would require to design the reactor including the bushings with an adequate oil-barrier system for the main insulation. In comparison to that, the upgrade of the main insulation of a dry type reactor is relatively simple and is achieved in principle by just extending the length of the support insulators and by providing the coil with adequate shielding electrodes to meet surge voltage and RIV requirements. Fig. 5 shows a prototype UHVDC dry type smoothing reactor in the test lab during dielectric testing.
The coil is post mounted on 12 composite type insulators having a length of about 10 m. The weight of the coil is about 30 tons. The number of insulators and their mechanical rating is governed by the seismic activity level anticipated at the area of installation. A post mounted coil as shown in the figure comes very close to a simple oscillator with one lumped mass represented by the mass of the coil and a spring resulting from the elasticity of the insulators. The earthquake force induced by vibration of the foundation into the structure is proportional to the mass of the reactor multiplied by the ground acceleration. The effective force depends on the resonance frequency of the structure as compared to the frequency range of the seismic vibrations with maximum acceleration. In case of such a heavy weighted coil mounted on long insulators the resonance frequency is well below the critical frequencies of earthquake vibrations which mitigates the seismic loading of the structure.

INTERNAL INSULATION

One major challenge for developing UHVDC main equipment is to appropriately design the converter transformer and its bushings. Severe transport limitations for the converter equipment to the rectifier station of the first UHVDC application results from the location in a hilly area at 1800 m altitude above sea level. In a very early stage of the UHVDC development process a transformer bushing prototype was designed and manufactured. Together with the oil-filled barrier system which represents the connection to the transformer tank, one of the most critical parts of the transformer design was set-up. A set of dielectric type tests have been conducted in August 2005 at the Technical University of Graz. Successful completion of the tests was essential to ensure adequacy of the design process as well as of the manufacturing capability. It presented one major milestone for proving feasibility of UHVDC to manufacturer and customer.

As an example for internal insulation design calculations of the electrical field in the transformer tank are shown below. The figures show the valve winding (white area in the centre) with shielding electrodes on the top (also white shaded in the figure) surrounded by oil (blue areas). On the outer border the (grounded) transformer tank is located. Within the oil so called grading rings are located which assist to form a uniform field. Different colours are used to illustrate field strength (red gives the highest field strength, dark blue the lowest). In order to give an insight into complexity of the design process the field distribution during a voltage polarity reversal is simulated. It can be clearly seen how the field changes with time. While the maximum field strength at begin of the process is
located directly at the grading ring on top of the electrode shield (above the hole in the electrode), the maximum strength after 1680 seconds is at the corner of the electrode shield. It is essential for a transformer manufacturer to know phenomena like these in order to be able to optimally design a transformer.

Figure 7: Electrical field distribution in converter transformer during polarity reversal

COMMERCIAL APPLICATION

The equipment design as described in this article is used for the world’s first commercial application. Currently the Yunnan-Guangdong ±800 kV UHVDC Project is under construction which has a rated power of 5000 MW (3125 Amps). It connects the AC networks of Yunnan province in south-west China and Guangdong province in south China. The two converter stations are located in Chuxiong (Chuxiong Station) in Yunnan province and Suidong (Suidong Station) in Guangdong province. Several existing HVDC transmission schemes at ±500 kV operating voltage level already exist in the same region and terminate all in the Guangzhou area: Tian-Guang HVDC scheme, Gui-Guang I and Gui-Guang II HVDC schemes.

Figure 8: Converter Transformer for Yunnan-Guangdong Project in test field
The converter equipment’s withstand voltages and test values have been calculated based on IEC standards and are summarized in the following table:

<table>
<thead>
<tr>
<th>test/design values</th>
<th>Transformer 800 kV valve side</th>
<th>Transformer Bush. 800 kV valve side</th>
<th>DC Wall Bushing</th>
<th>800 kV DC Yard Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>switching impulse protective level</td>
<td>1344 kV</td>
<td>1344 kV</td>
<td>1344 kV</td>
<td>1330 kV</td>
</tr>
<tr>
<td>(ratio SIPL/SIIV)</td>
<td>1.19</td>
<td>1.31</td>
<td>1.19</td>
<td>1.20</td>
</tr>
<tr>
<td>lightning impulse protective level</td>
<td>1344 kV</td>
<td>1344 kV</td>
<td>1344 kV</td>
<td>1579 kV</td>
</tr>
<tr>
<td>(ratio LIPL/LIIV)</td>
<td>1.34</td>
<td>1.47</td>
<td>1.34</td>
<td>1.23</td>
</tr>
<tr>
<td>ac withstand test voltage</td>
<td>905 kV</td>
<td>1054 kV</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>de withstand test voltage</td>
<td>1250 kV</td>
<td>1455 kV</td>
<td>1200 kV</td>
<td>1200 kV</td>
</tr>
<tr>
<td>polarity reversal test voltage</td>
<td>965 kV</td>
<td>1124 kV</td>
<td>1000 kV</td>
<td>1000 kV</td>
</tr>
</tbody>
</table>

It should be noted that design of the equipment additionally had to take into account an installation altitude at 1850m above sea level at the rectifier station. Therefore, test values for external insulation verification had to be corrected according to the corresponding testing location.

BIBLIOGRAPHY
