MODERN HVDC THYRISTOR VALVES

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1 Introduction

The modern HVDC converter valve is air insulated, water cooled and suspended indoors in a controlled environment. The four single valve functions connected to the same AC phase in the 12-pulse bridge are mounted on top of each other in a quadruple valve arrangement. The valve arresters are similarly suspended adjacent to the valve structure, connected directly to the terminals of the valves. The quadruple valve is designed to meet seismic requirements. Field experience as well as full scale tests during the commissioning stage have proven the adequacy of the seismic design tools.

The thyristor is always custom designed. It is specified to withstand all electrical and mechanical stresses during type testing and operation. Optimized thyristor design is used to reduce the on-state losses. Due to improved di/dt and dV/dt capability of the semiconductors, the damping circuit arrangement has been simplified. 9 kV devices are currently employed in HVDC plants, and the 5” high current device developed will be installed in a commercially operated plant during the autumn of 1996.

The modern quadruple valve structure allows thyristors to have up to 10 kV forward blocking voltage. Modern computer tools and full scale dielectric tests have resulted in design guidelines for proper clearance to valve hall walls and adjacent structures for applications also above 600 kV DC voltage.

2 Converter Valve Structure

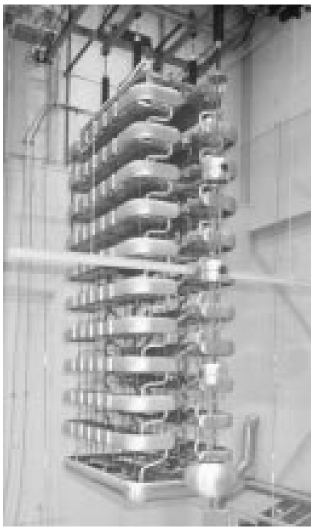

Fig. 1 Leyte -Luzon quadruple valve in test hall.

The quadruple valve structure is suspended from the ceiling of the valve hall via porcelain insulators. At the top and bottom of the structure, a metallic framework ensures the mechanical stability of the valves. Between the frameworks, the different levels in the valve are mechanically fixed by means of threaded epoxy rods. The design allows easy assembly in addition to giving a balanced design with regard to earthquake considerations.

The series connected thyristors in each valve function are mechanically arranged in modular units. Each modular unit is served by one valve reactor module. The modular units are arranged in different layers within the structure, each layer containing four thyristor modules and four reactor modules.

Within each level, the four thyristor and reactor modules are arranged in a rectangular shape, with two thyristor and reactor modules on each side of a central shaft running vertically through the valve structure. In this shaft, workman platforms are positioned on selected levels for easy access and maintenance purposes. The platforms are made of insulating material and represent a part of the mechanical structure.

Cooling water distribution pipes and light guides for signal transmission are shaped to maintain demands for creepage distance between the different voltage levels in the valve. The potential of the cooling water in the distribution pipes is controlled by means of electrolytically inert electrodes (platinum).

3 Seismic Design

Extensive experience has been gained of installing converter valves in seismically active areas. The design with a suspended valve structure has proven to be very suitable with regard to seismic considerations. An advanced model for the standardized design of the valve structure has been developed, based on the finite element program RAMSES, developed by ABB Corporate Research. Verification of the model has been performed by snap-back tests on complete quadruple valves.

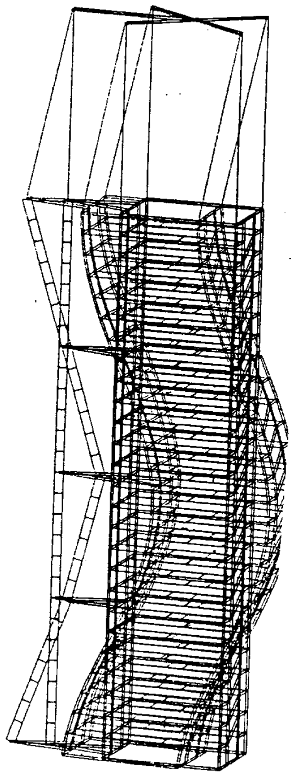

Fig. 2 Simulated dynamic behaviour during earthquake.

4 The Valve in the Valve Hall

The distance between a converter valve and its surroundings cannot be determined from voltage magnitude and wave shape alone. Certain factors must be taken properly into account, e.g the physical appearance of the valve structure and also the adjacent structures, due to combined electric fields. For example, a corona shield experiences electric fields vertically and horizontally in relation to adjacent corona shields, but is also subject to the field towards the valve hall walls or other valve structures.

The decisive external stress for a quadruple valve is usually an overvoltage of switching type. HVDC converters of 500 kV and higher have insulation levels well above 1000 kV. Increasing thyristor voltage capability results in higher layer-to-layer voltage. These factors taken into consideration, studies and tests have been performed to ensure proper behaviour of the quadruple valve during type testing and operation.

Using a Boundary Element Method program, linked to the CAD computer, combinations of field strengths and external distances have been used to optimize the corona shields. The calculations have been verified through extensive testing for a range of combinations of external distances and applied switching surge. In this connection, verified design tools have been obtained to optimize valve hall distances for plants with all DC ratings, even beyond 600 kV.

5 Basic Electrical Design

The converter valves and its components is to withstand all kinds of current and voltage stresses during steady-state operation as well as faults, not to forget the stresses imposed during valve type testing. The valve stresses are determined from the main circuit data for the transmission, such as maximum ideal no-load voltage (U_{di0max}), maximum continuous direct current (I_{dmax}) and the arrester protective levels. The dielectric stresses of the thyristors are commonly divided into single and repetitive stresses; single referring to fault conditions.

The basic design formula for the thyristor voltage parameters is:

$$V_{thy} = U_{max} \times k_d \times k_r \qquad (1)$$

where k_d is the uneven voltage distribution factor and k_r is the redundancy factor.

U_{max} may be either single or repetitive stress, in forward or reverse direction. Typically, the calculation of the direct single maximum voltage (V_{DSM}) is based on the arrester protective level. The uneven voltage distribution factor includes tolerances in damping circuit components, thyristor recovery charge and difference in resistance of cooling water circuits. The redundancy factor equals the total number of thyristors divided by the number of thyristors remaining when all the redundant thyristors have failed.

The maximum repetitive stresses are to take the commutation overshoots into account, also under dynamic overvoltage conditions. Operation at high firing angles must be considered. Although limited in duration, operation at high firing angle plus maximum dynamic overvoltage results in maximum repetitive stresses. The valve arresters usually have an attenuating effect on the commutation overshoots for this operating mode.

It is common practice within the industry to add an insulation margin on top of the maximum calculated stresses for electrical equipment, converter valves included. However, there are benefits in reducing the insulation margin for a converter valve, in the forward direction. The thyristors employed inherently have a higher voltage capability in the reverse than in the forward direction, approximately 10%. It is feasible to reduce the insulation margin in the forward direction due to the very reliable protective circuits in today's thyristor control units (valve electronics). This philosophy has been used by ABB in most HVDC projects over the last ten years.

6 The Thyristor

The valve's electric design allows a fully optimized thyristor. The semiconductors are optimized for each HVDC project with respect to voltages and especially the on-state losses.

Very high voltage thyristors have been available for some time. Today it is economically feasible to use these in commercial HVDC plants. Improved processing techniques and more sophisticated wafer design have increased the voltage withstand capability as well as the capability of handling voltage and current derivatives. Today, ABB uses 9 kV devices for plants with current ratings in the lower range, e.g. the Leyte-Luzon project in the Philippines.

A higher voltage rating means a thicker silicon wafer. For a given area and current, the increase in thickness means higher losses and reduced surge current capability. In addition, increased DC current demands result in higher valve short circuit current. These demands combined have led to demands for a larger wafer area.

Recently, the 5", 3.6 kA, 8.8 kV thyristor was developed. Being a major development step, a test installation will be made in a commercial HVDC plant, besides the extensive test programme at the manufacturing plant. The approach of field testing is in line with ABB's philosophy, following test valves at Sylmar (USA), Vester Hassing (Denmark) and Stenkullen (Sweden) converter stations.

The power handling capability of HVDC thyristors is growing rapidly, as shown in Fig. 3. The failure rate is low, and has to date never resulted in a forced outage at any plant that has individual thyristor protection. According to the latest Cigré statistics, the average annual failure rate for the 35,000 devices installed is only 0.12%.

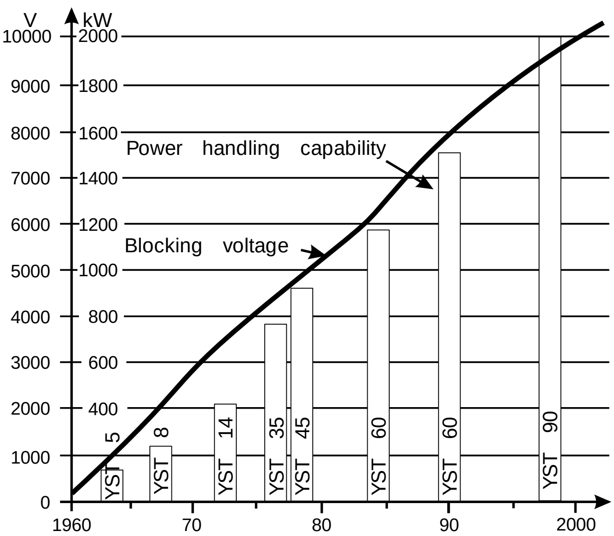

Fig. 3 Thyristor blocking voltage and power handling capability.

7 Thyristor Control Unit (TCU)

The thyristor control units constitute the optical/electrical interface in the valve between the control system and the thyristors. A robust and independent design is essential for the TCU in order to ensure reliable in-service performance.

The main features of the TCUs are:

- metal encapsulation, providing good protection against electromagnetic interference
- electronic components chosen for high reliability
- quick recharge of energy for electrical gate pulses
- very accurate protective firing function with dV/dt-dependence
- protective firing of de-energised valve in the event of both switching and lightning surges
- supplementary protective firing function during the sensitive thyristor recovery interval
- thyristor status monitoring - including indication of protective firing.

More than 20,000 units of the same basic design are operating in HVDC plants today.

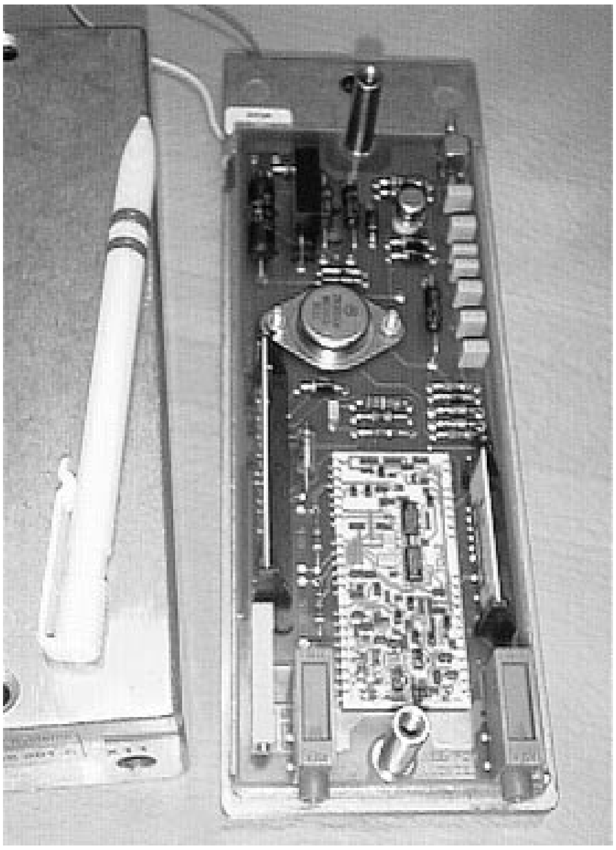

Fig. 4 Thyristor control unit.

8 The Thyristor Module

The modern ABB valve uses the well-proven concept of physical modules containing six thyristor positions, allowing easy handling during assembly and upon site installation. The thyristor package is rigidly clamped together by means of two glass fibre reinforced clamping slings, with disc springs allowing thermal movements. The clamping slings have proven to have excellent performance in the field.

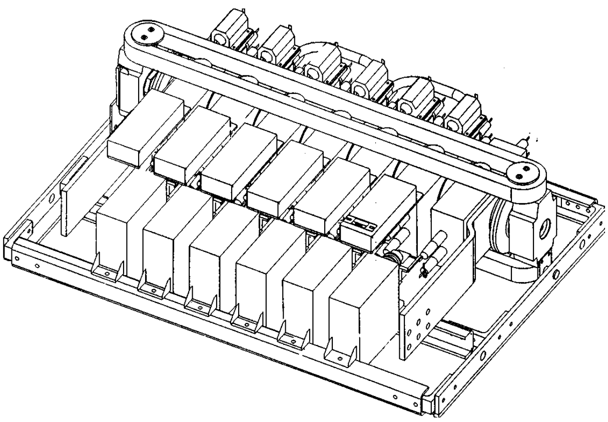

Fig. 5 Thyristor module.

Cooling of the thyristors is achieved by heat sinks, designed to reduce the thermal resistance between thyristor wafer and the cooling medium to a minimum. The increased power handling capability of the devices means higher on-state losses, and consequently the thermal resistance becomes an increasingly important parameter as the impact on the cooling system design is large.

The improved dV/dt capability of the thyristors results in one RC damping circuit, with an additional DC dividing branch. Power to the thyristor control unit (TCU) is extracted from the RC-damping circuit. The resistors are mounted in contact with the thyristor heat sinks to allow easy removal of the heat dissipated in the resistors. The capacitors are of dry type.

The routine tests include electrical and thermo-mechanical checks, as well as testing of the firing and protective functions of the thyristor control unit. After valve assembly is completed at site, all thyristor positions are checked once more using the high voltage Valve Test Unit, in an automated sequence.

Valve reactors are used to limit current and voltage derivatives for the thyristors. The reactors are of robust design, with the active parts totally embedded in insulation material. This design reduces mechanical stresses on the active parts of the reactor, while improving the thermal properties. Dissipated heat is efficiently removed by the cooling water through the hollow main current conductor.

9 Valve Cooling

The losses dissipated in the thyristor valves are removed by a cooling medium, this usually being deionized water. A single circuit system is used today, shown schematically in Fig. 6. The main circuit includes an extra pump for redundancy, outdoor coolers, a deaeration vessel (gas scrubber) and interconnecting piping. A few per cent of the water is passed from the main flow into the water treatment circuit, with two ion exchangers and an expansion vessel.

The two ion exchangers are connected in series. Besides taking care of water volume changes with temperature, the expansion vessel features level gauges for leakage detection and also serves as an oxygen removal device. The cooling system protection software includes three different leakage detection principles, one of which captures leakages less than one litre per hour.

The thyristor wafer has a limited thermal capacity. Thus, the maximum design temperature of the thyristor is to be chosen sufficiently low to allow a valve short circuit to occur without loss of thyristor life. This design temperature must not be exceeded under any operating conditions.

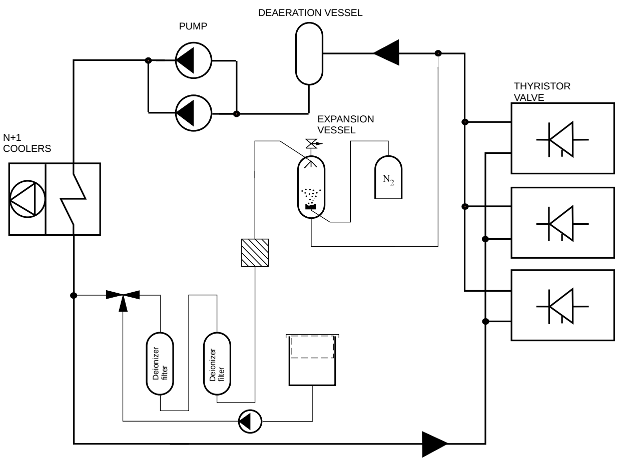

Fig. 6 Single circuit cooling system with water treatment circuit.

The thyristor wafer design temperature, thyristor losses and the maximum ambient temperature determine the size of the cooling system.

In steady-state conditions, the difference in temperature between the wafer and the water is determined by the relationship:

$$\Delta T = P \times R_{th}, \quad (2)$$

P being the thyristor losses and R_{th} the thermal resistance.

Reducing the thermal resistance results in lower ΔT, allowing higher water temperature with constant wafer temperature. Hence the “operating temperature” of the cooling system is higher, allowing a dry type, single circuit, closed loop system to be used in warmer climates.

In areas where freezing could occur, pure glycol is added to the water. Should the freezing risk be of a temporary nature, electrical heaters are instead provided to heat the water on those rare occasions when the temperature is below zero and the converter is not operating.

If overload capacity is specified for transmissions at all ambient temperatures, the cooling system must be enlarged accordingly. Then the steady-state operating temperature of the thyristor must be reduced. During the overload the wafer design temperature must not be exceeded.

10 Testing

Apart from the routine tests, one complete thyristor valve for each HVDC project is type tested according to one of the standards IEC 700 or IEEE 857.

The dielectric type test programme includes DC and AC tests with measurement of partial discharge, and impulse tests with standard wave shapes. These tests are usually performed on both a single valve and the quadruple valve arrangement.

The operational tests, i.e.,, the current related tests, are performed in an in-house back-to-back test circuit, with one six-pulse bridge acting as rectifier and the other as inverter. With this type of test circuit, passive generation of the voltage and current waveshapes is affected, which ensures that appropriate test stress conditions are obtained. The circuit is fed from a 1000 MVA short circuit generator. The reactive power balance is taken care of by filters and shunt banks. Today the MACH control system is used for the back-to-back circuit, so that power ramps, control angle shifts and sequences of these, etc., can be pre-programmed.

11 High Angle Supervision (HAS)

Some HVDC transmissions are basically used to transmit bulk power. The converters are operated continuously at low firing and extinction angles, and only occasionally are higher angles used. The HAS concept was developed to increase flexibility in meeting reactive power demands.

The HAS concept is based on continuous on-line monitoring/calculation of valve parameters to ensure safe operation. However, it is not necessary to limit each individual operation parameter, which results in a more optimized utilization. Parameters such as valve arrester voltage, thyristor wafer temperature and snubber resistor losses are indirectly monitored. In principle, the instantaneous power dissipation is calculated for all sensitive components. The energy absorption is then compared to inverse-time characteristics.

The HAS concept was introduced for the Kontek transmission, greatly improving the response to sudden changes in reactive power demands.

12 Fire safety

The design of the thyristor valves includes a variety of insulating materials which are needed to fulfil requirements regarding electrical insulation and mechanical stability. For this purpose, both reinforced and unreinforced polymeric materials are used, due to the useful combination of good dielectric properties, low density and adequate moulding and machinability. Materials reinforced with higher contents of glass fibre have mechanical properties comparable to aluminium and sometimes steel. Hence there are obvious reasons for using polymer based materials and there is no realistic substitute for them.

The design philosophy for fire safety of ABB thyristor valves was developed in the early nineties and adheres to the more recent conclusions from Cigré work (TF 14.01.04). The development has included extensive analysis of possible scenarios, selection and testing of suitable materials and components, and testing of complete thyristor valve structures. The design is based on the following:

- Only a minimum number of electrical connections, carefully designed with large safety margins. All main circuit connections made with bolted or welded joints.
- Selection of valve material that cannot maintain a fire, i.e., the materials have low flammability and are self-extinguishing.
- Sectionalization of the valve by fire-retardant barriers, both horizontally and vertically.
- Early fire detection system, sensing an incipient fire condition.

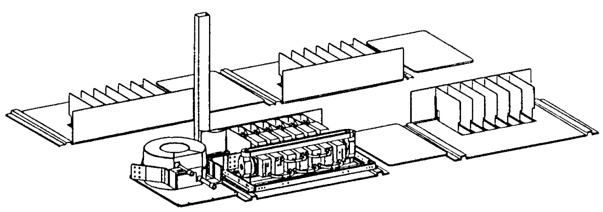

Fig. 7 Horizontal fire barriers separating layers and vertical barriers between thyristor positions.

The actual design of the ABB valve has successfully undergone practical fire tests in full scale test set-ups.

General experience concerning fire propagation, in combination with experience from practical fire tests in valve mock-ups, reveals that a fire mainly propagates vertically. Sectionalization of a structure by means of horizontal barriers, combined with effective gas evacuation, is the most suitable design with regard to fire safety.

The design of the ABB thyristor valve structure is thus based on sectionalization between adjacent valve layers by means of horizontal fire barriers, in combination with an open vertical shaft in the centre of the valve. The open shaft serves as evacuation channel for smoke and gases, and ensures fast detection of an incipient fire condition by the smoke detection system sensors positioned right above each valve structure. The service platforms positioned in the middle shaft are made semipermeable to allow smoke to pass through.

For the structural parts of the thyristor valves, major efforts have been devoted to increasing the fire withstand properties of the materials, without cutting back on the demands regarding mechanical and electrical properties.

New polymeric materials, containing Alumina Tri Hydrate ($Al(OH)3$) as a fire retardant additive, have been developed within the ABB Group for this purpose. Materials and manufacturing methods are specially designed to suit thyristor valve applications.

In the modern ABB valve, the number of components and electrical connections are reduced to a minimum.

The thyristor valves are suspended from the ceiling via high temperature resistant insulators. The suspension insulators are glued to the brackets by Portland Cement and have been proven through testing to be capable of withstanding temperatures higher than those calculated as maximum levels in the event of fire.

The light guide bundles are protected by a channel made of fire retardant material (pultruded glass fibre reinforced polyester). Furthermore, the channels are sectionalized by using fire retardant sealing bags along cable jackets in channels and inlets.

13 Conclusion

The modern HVDC converter valve has been designed for high reliability and availability. Essentially based on the earlier well proven generation, the modern valve adds features such as:

* implemented fire safety measures in valve design and choice of materials
* improved plant utilization through the HAS concept
* simplified voltage sharing circuits
* single circuit cooling system
* improved water leakage detection
* higher thyristor voltage and current rating.