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Reliability Enhancement of HVDC Transmission by Standardization of Thyristor Valves and Valve Testing

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Abstract — **After more than thirty years development bulk power transmission by means of HVDC thyristor valves has become an industry standard. Concept of standard thyristor valve design has been adopted in many HVDC projects for reliability enhancement in recent years. Choosing of standard components, using well-proven design structure and rigours valve design verification program and test circuit are the three most important aspects for thyristor valve standardization. Statistics has shown a significant decreased outage rate of thyristor valves after the implementation of valve design standardization.**

Index Terms — **HVDC transmission, HVDC thyristor valves, design standardization, reliability**

I. Introduction

Bulk power transmission by means of High Voltage Direct Current (HVDC) has become an industry standard. As the main equipment in HVDC transmissions, the thyristor valves challenge, therefore, for even higher reliability and low cost.

Traditionally, design of HVDC thyristor valves involves the design of each component used in the entire valve and the way to connect them together. Among those components, thyristor design is one of the most critical processes. Historically, the continuous development of the thyristor in term of power handling capability, voltage withstand capability and production technology made new valve designs economically favorable in relation to reusing old design.

Today, except the 6” thyristors for future 800kV transmission projects, development of silicon-based thyristors becomes maturity. Well-proven thyristor and valve designs for most applications have been established and their reliability was proven by more than thirty HVDC installations worldwide. The focus should therefore pay on the reliability enhancement and cost reduction by valve design standardization.

The HVDC thyristor valve design standardization includes the valve component standardization, valve design standardization and valve test program and test circuit standardization.

Component design standardization involves all the components used in a converter valve such as thyristor, thyristor control unit (TCU), snubber capacitor, snubber resistor, d.c. voltage measuring resistor, saturable reactor, heat-sinks and valve arrester.

Valve design standardization includes valve electrical design standardization and valve mechanical design standardization two aspects. Snubber circuit design, TCU design and over-voltage protection coordination are the main issues for valve electrical design standardization. Arrangement of series connected thyristors, cooling of thyristors and valve installation are the main tasks for valve mechanical design standardization.

Laboratory verification is an inseparable part of HVDC thyristor valve design standardization. Test program has been specified in a detail way in both IEC 60700-1 [1] and IEEE 857 [2]. Both six-pulse back-to-back test circuit and synthetic test circuit based on a parallel current injection method have been used as standard test circuits for the operational tests of valve [3].

The thyristor valve standardization philosophy has been implemented in numbers of HVDC projects. Statistics from these projects have shown a great reduction in the thyristor valve outage in service with a failure rate of a thyristor level less than 0.1% annually. The cost of the valves and valve hall has been significantly reduced simultaneously.

II. Components of HVDC Valves

A. High Power Phase Control Thyristors

Past thirty years development on the semiconductor product has resulted in mature thyristor product available for various HVDC and SVC applications nowdays. These electrically triggered thyristors (ETT), Figure 1, are

Fig. 1 Modern thyristor with silicon wafer

Fig. 2 TCU electronic circuit board

characterized themselves in high reliability. There is only one thyristor failure reported among eighteen thousands pieces in service in HVDC application. These electrically triggered thyristors are voltage categorized on 6.7kV, 7.2kV and 8.5kV corresponding to extra high, high and medium high conducting current respectively.

A 6" wafer based 8.5kV thyristor is on the way out for bulk power transmission in 800kV UHVDC transmission projects and future Back-to-Back HVDC applications [4]. This new thyristor inherits the design and quality control philosophy in manufacturing. This new thyristor is expected to be of the same reliable performance as those in service.

Light triggered thyristors (LTT) had been developed in 1980's. Over-voltage protection function has been successfully implemented inside a LTT over the last two decades but not the high dU/dt related recovery voltage protection. External protection circuit at high potential is needed even today. Due to the complex manufacturing process of LTT and auxiliary circuit necessary for recovery protection reliability of LTT based HVDC is subjected to being verified by more installations.

B. Thyristor Control Unit

The low thyristor failure rate is not contributed by high quality thyristors alone but the control and protection provided by the thyristor control unit (TCU) as well.

Thanks to the electronic industry, the thyristor control unit (TCU) undertook a revolutionary progress both in function and physical size since the first generation. Modern TCU provides even more comprehensive functions at a great reduced number of components and operation losses [5].

One of the most important features is the TCU's controllability after blackout. As soon as forward voltage or positive voltage derivative across the thyristor level appears the TCU can be energized and is ready to receive firing command and to provide local protection of thyristor. The TCU functions multiply as a thyristor monitoring unit due to the integration of a measuring electronic circuit in the electronic board.

C. Capacitor and Resistor in Damping Circuit

Nitrogen (N_2) based gas filled dry type capacitors are the state-of-the-art as the snubber capacitors of thyristors. The pressure relief valve design of the capacitor can further eliminate the flame risk of snubber capacitors.

Snubber resistors are water cooled in HVDC application. The same aluminum heat sinks for thyristors are used to cool those tubular snubber resistors since they are inserted directly in the tubes serviced for resistor cooling on the heat sinks.

D. Saturatable Reactor

Saturable reactors, green object in right side of Fig.3, are built with 5 turns of hollow water

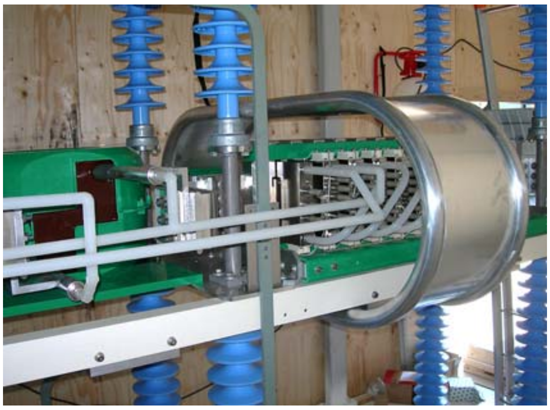

Fig. 3 Saturable reactor and thyristor module assembled in an enclosure installation

cooled conductor and numbers of ferrite cores. Polyurethane rubber is filled to enforce the mechanical strength of reactor and damping out electro-magnetic noise. A glass reinforced polyester cover is used to isolate the reactor live part from adjacent components.

E. Valve Arrester

Valve arresters are configured with numbers of arrester blocks in series connection for protection level requirement and in parallel connection for energy requirement. Arrester blocks are made of highly non-linear ceramic resistor material composed for the most part zinc oxide (ZnO) mixed with other metal oxides and sintered together.

III. VALVE ELECTRICAL DESIGN

A. Thyristor and Associated Circuits

The choice of thyristors in one HVDC project is the result of optimizing processes in HVDC station design and thyristor valve design. Losses and cost are the main concerns in the optimizing process.

After the right thyristor is selected other associated standard components' data such snubber capacitor capacitance, snubber resistor resistance and TCU protection level can be defined. Except the thyristor valves used in 800kV not much attention should be paid on the shield of valves as they are standard designed to cover valve application with a voltage rating up to 600kV.

B. Thyristor Over-voltage Protection

Valve arrester is the main over-voltage protection means for thyristor valves in forward direction and reverse direction. The protection level of valve arrester is coordinated with the number of thyristors in series connection to ensure the maximum voltage across each thyristor unit under the thyristor specification. Both single voltage surge and repetitive surges during dynamic over-voltage shall be limited by the valve arrester.

Additional thyristor over-voltage protection in forward direction is provided by TCU for each individual thyristor. Whenever over-voltage or high dV/dt in forward direction is detected the TCU will produce a gate signal to fire the thyristor. This function secures thyristor when fiber optic communication channel is broken or valve internal fault arises.

IV. VALVE MECHANICAL DESIGN

A. Valve Module Design

For easy handling during assembling, upon site installation and valve maintenance, valve's module design has been proven to be apposite. Each thyristor module, Fig. 4, can contain multi thyristor positions. Typical number of thyristor positions in one module is nine.

Mechanically, the thyristors, with the heat sink in between, are rigidly clamped together by means of two glass fiber reinforced claming slings, with disc springs allowing their movements. The damping circuit resistors are mounted in contact with the thyristor heat sinks and the capacitors are of dry type and mounted on an insulator plate which is adjacent to the heat sinks as shown in Fig. 4.

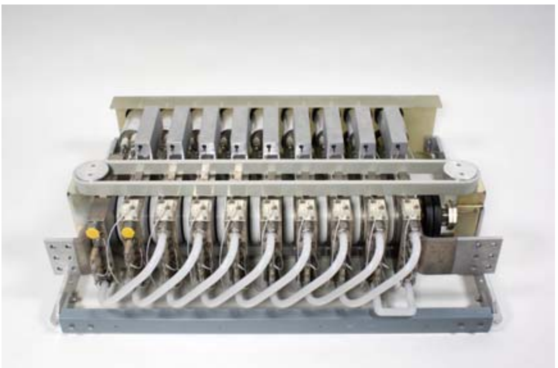

Fig. 4 Front view of HVDC thyristor module

B. Valve Cooling Circuit Design

De-ionized water has replaced pressured air and oil as the coolant for thyristor cooling for more than thirty years for its high cooling efficiency and insulation characteristics. In order to maximum use the power capacity of thyristor the thyristors are always adjoined with aluminum heat-sinks. Cooling water circuits to each aluminium heat-sink in one thyristor module can either be in parallel connection or be in series connection. At the same cooling flow rate the series connection of cooling circuits, Fig. 4, reduces the number of junctions to about half that used in a parallel connection for a same cooling effect for all thyristors. The parallel cooling minimizes the risk of water leakage of thyristor modules.

The inlet cooling water pipes and outlet cooling water pipes of thyristor modules in one valve structure are connected to the main water supply and return pipes in parallel.

C. Valve Structure and Valve Suspending Installation

The thyristor modules and reactors modules are connected in series and arranged in a rectangular pattern with each four thyristor modules lied in one valve layer. The two thyristor modules on each side of the rectangular shape layer are designed with all cooling liquid connections located at the outer sides of the valve, inside the corona shields. In the event of leakage the cooling liquid is forced out of the valve, away from active components. In the middle of the layer, there is a central shaft running vertically through the structure for maintenance purpose. The valve arrester (black cylinder beside each valve in Fig. 5) is hanged on the same valve structure out of the layers.

Fig. 5 Suspended valve installation at LongQuan converter station of Three-Gorges — ChangZhou HVDC transmission project

By the increase of power handling capability of HVDC thyristors and snubber capacitors the valve size minimization is achieved. One valve structure containing two or four single valves is a standard design for HVDC transmission applications. The choice of double valve (two valves in one valve structure) or quadruple valve (four valves in one valve structure depends mainly on the local building code and converter transformer design.

In seismically active areas installation of converter valves needs to be carefully designed. Study and experience have proven a suspended valve structure, Fig. 5, is a good solution [6]. Valves shown in Fig. 5 are with a double valve design.

V. Valve Design Verification

Voltage and current stresses on HVDC valves have been described in Cigré technical publication [7]. To verify the valve design these stresses have to be reproduced in different test duties in the test laboratory by the type test program specified in IEC60700-1 [1] and IEEE857 [2]. Conclusion drawn from test and service experience over last thirty years indicates that the test duty and test parameter determination method are adequate. By the right choice of test circuits valve malfunction due to improper use of components or inappropriate valve design can be found at an early stage.

A. Dielectric Tests

Dielectric tests are intended to verify voltage withstand and voltage-related characteristics of the valve under various over-voltage conditions. d.c. voltage test, a.c. voltage test, switching impulse test and lightning impulse test are applicable for dielectric tests of valve support, multiple valve unit (MVU) and single valve. Steep-front impulse test between valve terminals is a supplement of valve dielectric performance verification.

For single valve, the impulse tests should be done under two cases with valve TCU pre-energized and non-energized respectively in order to represent valve service conditions. One pre-charge circuit is needed for pre-energized valve impulse tests.

It is ideally to have valve temperature / thyristor junction temperature representative of the most critical stresses at all tests. This would, however, involve an unnecessary extra cost. Since the forward blocking voltage withstand capability of thyristors is highly sensitive to rapid rise of voltage and decreases with increasing junction temperature [8] and the electronic circuit made TCU may be susceptible to spurious behavior under high rate of rise of voltage and hot valve condition, lightning impulse test and steep-front impulse test at hot valve condition are of special interesting. A third circuit should be used in the test arrangement to preheat test valve in those tests.

B. Operational Tests

Operational tests are intended to verify the design of the valve regarding its performance under normal conditions, abnormal conditions and transient fault conditions. As both high current and voltage present the operational tests on a complete valve are impossible. Instead test on valve section consisting of minimum five thyristor levels is accepted.

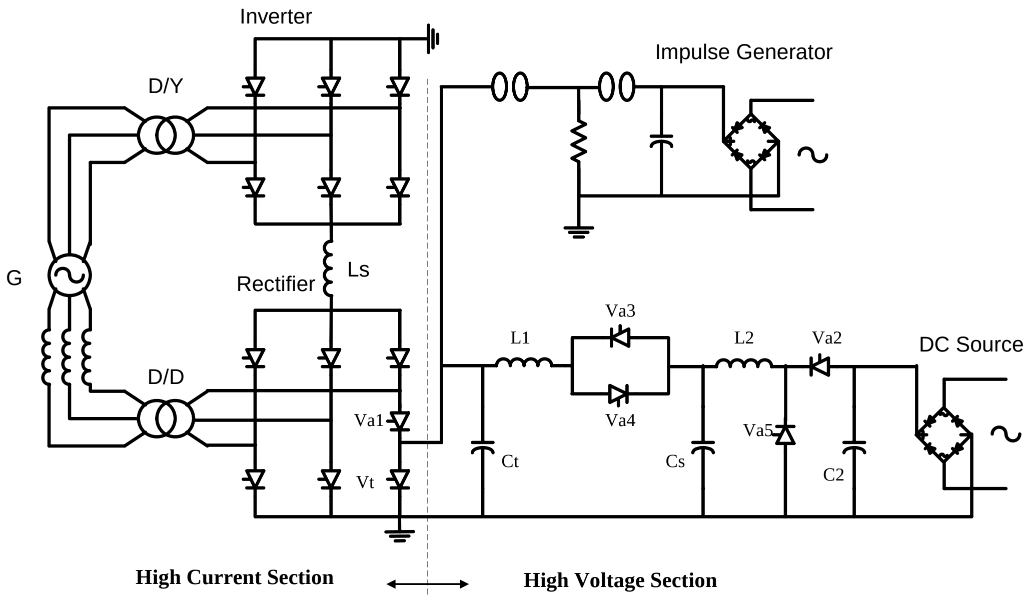

Fig. 6 Synthetic test circuit for test of modern HVDC thyristor valves

A six-pulse back-to-back test circuit, High Current Section of Fig. 6, is of the highest test equivalence for operational test of valve section because it is scaled down directly from the actual converter station.

To expand testing power in operational test by means of synthetic testing is a technical sound and economical wise solution if the synthetic test circuit is properly designed.

A current injection method based synthetic test circuit, Fig. 6, incorporated a conventional six-pulse back-to-back circuit and a voltage oscillation circuit, inherits the high test equivalence of conventional six-pulse back-to-back test circuit and offers more flexibility in development test [8] [9]. Synthetic testing circuits with the same operating principle have been accepted as standard test circuits by manufacturers and users in valve design verification.

VI. Summary

HVDC transmission plays a more and more important role in modern electric power transmission. A great attention has been paid on the development of thyristor based converter valves. The valve design standardization is one of the great progresses that HVDC converter valves undertook in the past decade. The thyristor level failure rate has been reduced to less than 0.1% per valve annually. There is only one thyristor level failure reported from ABB's eighteen thousands thyristor levels in operation in the last years.

Benefits acquired from valve design standardization are not only for reliability enhancement of HVDC transmission systems but also for cost reduction of converter valves.

VII. References

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VIII. Biographies

Baoliang Sheng was born in Changchun, China in 1961. He obtained his B.Sc degree in 1982 from Xi’an Jiaotong University, China, and his Ph.D. in 1995 from Delft University of Technology, the Netherlands, both in electrical engineering. From 1982 to1992 he was a test and research engineer at the National High Power Laboratory (XIHARI), China. He worked at KEMA as a research engineer and pursued his Ph.D. at Delft University of Technology from 1992 to 1996. He joined ABB’s High Power Laboratory at Ludvika, Sweden, in May 1996. He has been with ABB, HVDC, since 2000 as a design engineer of HVDC thyristor valves and FACTS controllers. He was appointed as Company Specialist in the area of High Power Testing of Electrical Power Equipment in 1999 and Senior Specialist in test of HVDC and SVC converters in 2004. He is Senior Member of IEEE. He is convenor of IEC SC22F WG15 and active member in several IEC working groups on HVDC valves and SVC valves.

Hans-Ola Bjarme was born in Stockholm, Sweden, in 1949. He obtained his Master’s degree from Royal Technical University, Sweden in 1976. He was a college lecturer in Stockholm from 1977 to 1982. He joined ASEA in 1982 as a research and development engineer. From 1990 to 1995 he had been with STRI (Swedish Transmission Research Institute) as a research scientist and project manager. From 1995 to 1997 he was a development engineer in ABB Power Transmission, Australia. Since 1997 he has been working in ABB, HVDC, as the manager of converter valve Electrical design department.

Hans Johansson was born in Lidköping, Sweden in 1961. After his technical school study he joined ASEA, HVDC 1982 as a research and development engineer. From 1984 to 1994 he worked at Siemens in Stockholm in different positions within X-ray equipment research and development division. From 1994 to 2000 he was manager for development and design of high voltage bushings at ABB Power Products, Components. During 2001 he was project manager for the development of a new generation of Voltage Sourced Converter valves at ABB Technologies, Power Systems. Between 2002 and 2004 he was marketing manager at ABB Power Products, Components. Since 2005 he has been working at ABB, HVDC, as general manager for the converter valve department.