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Converter Valve Design and Valve Testing for Xiangjiaba – Shanghai ±800kV 6400MW UHVDC Power Transmission Project

Baoliang Sheng, Jonatan Danielsson, Yanny Fu and Zehong Liu

***Abstract* — Thyristor valve design merits are inherited and new developed high power rating thyristors are used in the valve design. The thyristor control unit (TCU) and snubber circuit are optimized for a high reliability and low loss of thyristor valves. Two 12-pulse converters are connected in series as one converter per pole. The converters use a double valve MVU structure.**

A careful designed rigorous type test program has been followed to verify the valve and converter design. A single valve is comprehensively dielectric type tested and operational type tested. High voltage valve hanging structure, low voltage valve hanging structure and MVU, plus the series connected valve simulator, are valve supporting structure dielectric tested and MVU dielectric tested. The test results indict that the valve voltage and converter design and protection are proper and there is a substantial margin in operation since, for most of the operational tests, the test parameters were globally more severe than specified.

***Index Terms* — Xiangjiaba – Shanghai ±800kV UHVDC, HVDC converter, thyristor valve design, thyristor valve dielectric test, thyristor valve operational test**

I. Introduction

ABB was granted to design and manufacture the converters used in the inverter station, Fengxia substation, for the first ±800kV 6400MW bulk power transmission project. Converter in this project comprises of two 12-pulse thyristor valves in series connection per pole. Those two 12-pulse thyristor valves are installed in a low voltage (0 – 400kV d.c.) valve hall and a high voltage (400kV – 800kV d.c.) valve hall respectively to build up the 800kV pole d.c. voltage.

A double valve MVU structure is used to mount those valves in the valve halls. There are four MVUs in series connection per pole and phase with two of them located in the high voltage valve hall and the other two located in the low voltage valve hall. For a better transient over-voltage control on those MVUs surge arresters are connected from the top terminal of each 6-pulse bridge to ground, Figure 1.

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The design of 800kV thyristor valves uses all the state-of-the-art technologies in HVDC thyristor valve design, including high power rating 8.5kV 6” electrically triggered thyristors [1], thyristor module with compact design, and individual thyristor local over-voltage protection.

A comprehensive test program based on IEC 60700-1 [2] and client’s specification was followed in the valve design verification type test. A single valve exposed to the d.c. voltage test, a.c. voltage test, impulse voltage tests and non-periodic firing test in STRI’s high voltage laboratory. The thyristor modules in this single valve were operational type tested afterwards in ABB’s high power test plant in a 6-pulse Back-to-Back based synthetic test circuit.

Both high voltage (HV) MVU hanging structure and low voltage (LV) MVU were completely dielectric tested.

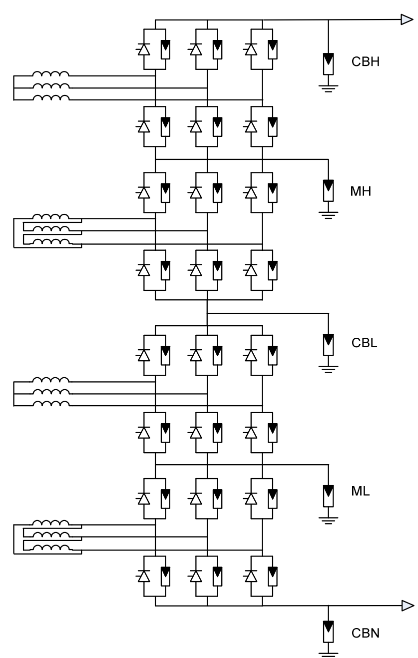

Figure 1 Converter valves and valve over-voltage protection scheme

The MVU dielectric test focused on the verification of voltage withstand capability to surroundings and the partial discharge levels being within specified limits. A pole potential MVU, together with a series connected valve simulator, was dielectric tested to verify the insulation of high potential 12-pulse converter in the HV valve hall and, the high potential MVU in the LV valve hall was dielectric tested with the same principle to verify the insulation of low potential 12-pulse converter in the LV valve hall.

II. Thyristor Valve Design

A. Thyristor valve requirements

Thyristor valves in Fengxian substation of Xiangjiaba – Shanghai 800kV UHVDC are operated fundamentally as an inverter with the possibility to operate them as rectifier when needed. Thyristor valve requirements are concreted by the client specification and system design. Requirements on the thyristor valves are given in Table 1.

Table 1 Thyristor valve requirements

Max. 6-pulse bridge voltage	204kV d.c.
Max. continuous current	4000A d.c.
2 h overload current	4400A d.c.
Peak over-current with subsequent blocking (one-loop fault current)	40.8kA
Peak over-current without subsequent blocking (three-loop fault current)	40.8kA, 42.2kA, 42.2kA
Firing delay angle at nominal power, α	5° – 17.5°
Extinction angle at nominal power, γ	17° ± 1°
Temporary a.c. system over-voltage load rejection factor with de-blocked valves	1.3
Switching impulse voltage protection level of valve surge arrester	386kV
Steep-front impulse voltage protection level of valve surge arrester	394kV

B. Thyristor valve design

6400MW bulk power transmission at ±800kV demands a high reliable converter. Thanks to the good performance records of thyristor converter valves in HVDC applications in the past decade many design merits [3] can be inherited directly in the design of 800kV thyristor valves. Successful development of high power rating 8.5kV 6” electrically triggered thyristors paved the way for a high current and voltage thyristor valve at a relative low quantity of thyristors in series connection.

A single thyristor valve comprising 56 pieces of 8.5kV 6” thyristors and their associated circuits can fulfil the requirements of Table 1 well. 2 of 56 are redundant. Those 56 thyristor positions are group assembled in eight thyristor modules with seven thyristors in each module.

Same as the valve design in Three-Gorges HVDC those thyristor modules are in series connection with reactor modules and layered up spirally as one complete single valve. The top end of this single valve terminates the bottom end of upper single valve. There are two single valves in series connection in each MVU.

Thyristor control units (TCU) used in this project have been modified to match the gate driving requirement of 6” thyristors. Heat sinks have been enlarged and coolant flow rate was increased in order to effectively dissipate the losses from thyristors. Other robust valve design methods, such as thyristor series cooling in one thyristor module and TCU energization by a tapped voltage branch, are kept.

C. Valve over-voltage protection design

Thyristor valve over-voltage protection is realized by valve surge arrester across each single valve and surge arresters installed on each bridge terminal to ground, Figure 1.

The thyristor snubber circuit parameter has been carefully determined to ensure an even voltage distribution of the series connected thyristor levels, whereas the total losses of valve have been controlled to the minimum.

The TCU provides an additional forward direction over-voltage protection and positive high voltage derivative protection by generating a firing signal to the gate of thyristor when the preset protective firing level or recovery protective firing level is reached.

This additional over-voltage protection is a local protection on each individual thyristor level without involving the remote valve control unit. This protection function secures the thyristor when one or several fibre optic communications are broken or valve internal fault arises.

III. Dielectric Test

A. Tests on a fully assembled single valve

These tests are performed on a complete valve equipped with eight thyrisitor modules. All valve components, except the valve surge arrester, in actual site installation are presented.

The tests and test parameters in the single valve test are as follows:

- d.c. voltage: ±320kV, 1 min. followed by ±260kV, 3 h (dry valve);
- d.c. voltage: ±260kV, 1 min. followed by ±160kV, 5 min. (wet valve);
- a.c. voltage: 273kV, 15 sec. followed by 187kV, 15 min.;
- Switching impulse voltage: ±425kV, 5 shots each polarity (dry valve + wet valve);
- Lightning impulse voltage: ±420kV, 5 shots each polarity (hot valve);
- Seep-front impulse voltage: ±471kV, 5 shots each polarity (hot valve);
- Non-periodic firing test: 5.3kA, 5 shots.

Test demonstrated that the valve protective firing took place between +427kV and +428kV, immediately above the surge protection withstand level.

Test results were quite a satisfactory and all tests were passed without any thyristor failure or component degradation.

B. Tests on valve hanging structures

Two valve hanging structures, differing mainly in length of insulators, are used in this project to suspend the low voltage (LV) MVUs (0 – 400kV d.c. voltage) and high voltage (HV) MVUs (400kV – 800kV d.c. voltage) respectively. The test program and test parameters adopted in the dielectric test of hanging structures are as follows:

For HV MVU hanging structure

- d.c. voltage: $\pm 979 \cdot k_{atm}$ kV, 1 min. followed by ±796kV, 3 h;
- Switching impulse voltage: $\pm 1161 \cdot k_{atm}$ kV, 5 shots each polarity;
- Lightning impulse voltage: $\pm 1270 \cdot k_{atm}$ kV, 5 shots each polarity.

For LV MVU hanging structure

- d.c. voltage: $\pm 326 \cdot k_{atm}$ kV, 1 min. followed by ±265kV, 3 h;
- a.c. voltage: $310 \cdot k_{atm}$ kV, 1 min. followed by 211kV, 30 min.;
- Switching impulse voltage: $\pm 558 \cdot k_{atm}$ kV, 5 shots each polarity;
- Lightning impulse voltage: $\pm 594 \cdot k_{atm}$ kV, 5 shots each polarity;
- Seep-front impulse voltage: $\pm 454 \cdot k_{atm}$ kV, 5 shots each polarity.

C. Tests on MVUs

The immediate connection of two single valves and tower design of MVU in ABB's valve structure physically waive the dielectric concern between two single valves as the dielectric strength between the two immediate connected layers of two single valves is lower than the one in single valve whenever in operation or in test. The MVU dielectric test therefore focused on the verification of external insulation of MVU, i.e, voltage withstanding capability of MVU to its surroundings and the verification of the partial discharge levels are within specified limits. To achieve this target the pole potential MVU was installed. For a correct voltage distribution representation in MVU test the other MVUs are substituted by valve simulators in test.

Different valve simulators are used in different test duties in order to create the correct voltage on the low potential terminal of test MVU. A pure water cooled d.c. resistor was used in the MVU d.c. voltage test, a capacitor was used in the MVU switching impulse voltage test and a group of series connected valve reactors were used in MVU lightning impulse voltage test.

Because the lightning impulse voltage isn't decisive for the determination of air clearance in ultra high voltage no lightning impulse voltage test was done on the HV MVU. Considering the LV MVUs (0 – 400kV) and HV MVUs (400kV – 800kV) are installed in different valve halls and have different air clearances in the design, test on MVU was repeated under different test arrangements and test levels. LV MVU was lightning impulse voltage tested.

The voltage levels used in the HV MVU and LV MVU dielectric test are listed below.

For HV MVU

- d.c. voltage: $\pm 1306 \cdot k_{atm}$ kV at high potential terminal and > $\pm 980 \cdot k_{atm}$ kV at low potential terminal, 1 min. followed by ±1061 kV at high potential terminal and > ±796 kV at low potential terminal, 3 h;
- Switching impulse voltage: $\pm 1600 \cdot k_{atm}$ kV at high voltage terminal and > $\pm 1161 \cdot k_{atm}$ kV at low voltage terminal, 5 shots each polarity.

For LV MVU

- d.c. voltage: $\pm 653 \cdot k_{atm}$ kV at high potential terminal and > $\pm 327 \cdot k_{atm}$ kV at low potential terminal, 1 min. followed by ±530kV at high potential terminal and > ±265kV at low potential terminal, 3 h;
- Switching impulse voltage: $\pm 788 \cdot k_{atm}$ kV at high potential terminal and > $\pm 558 \cdot k_{atm}$ kV at low potential terminal, 5 shots each polarity;
- Lightning impulse voltage: $\pm 863 \cdot k_{atm}$ kV at high potential terminal and > $\pm 594 \cdot k_{atm}$ kV at low potential terminal, 5 shots each polarity.

Figure 2 A high voltage MVU installed in the high voltage laboratory for dielectric test

IV. OPERATIONAL TEST

Valve operational test was performed on the thyristor modules in a 6-pulse Back-to-Back based synthetic test circuit, Figure 3, [4] [5]. Eight modules in one single thyristor valve have been type tested in four test set-ups respectively. Most of the test duties were conducted on two thyristor modules in every set-up. Maximum operating duty (α=90°) test, tests with transient forward voltage during the recovery period and valve fault currents tests were performed on one thyristor module each time.

The project design specification, Table 1, is used to determine the test parameters in the synthetic operational test. The test results reported in Table 2 are the values applied on one thyristor module. All the test duties reported in Table 2 started with a 10 minutes preheating with the heat-run test parameter after the specified test module(s) inlet cooling water is reached.

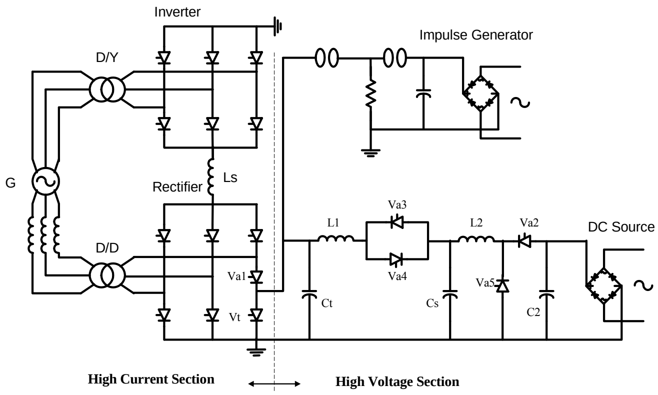

Figure 3 6-pulse back-to-back based synthetic test circuit

1μs, 10μs and 100μs front time impulses are used in the tests of transient forward voltage during recovery period. Five impulses of each type were applied in the recovery protection (RP) zone of thyristor control unit (TCU) and three additional impulses were applied immediately after the RP zone.

The objectives of the last test in Table 2, continuous protective firing, are to demonstrate the capability of continuous protective firing of TCU and the thermal capability of snubber circuit when fiber optic communication from ground potential valve control unit (VCU) to thyristor valve fails. This test is performed on one set-up with one pair of fiber optic disconnected to one thyristor position.

Test oscillograms acquired in the heat-run test, transient forward voltage during recovery period and one-loop fault current with subsequent blocking voltage are illustrated in Figure 4, Figure and Figure 6. The upper red colored curve in those oscillograms is the test voltage across the test module and the lower blue colored curve is the test current.

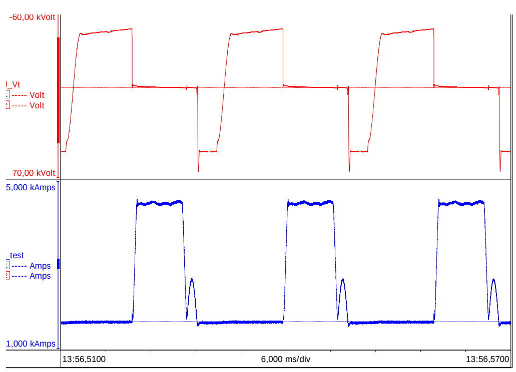

Figure 4 Periodic firing and extinction test / heat-run test (test set-up with two thyristor modules)

V. Tests for Valve Insensitivity to Electromagnetic Disturbance

Those tests were combined in the dielectric test in section III.

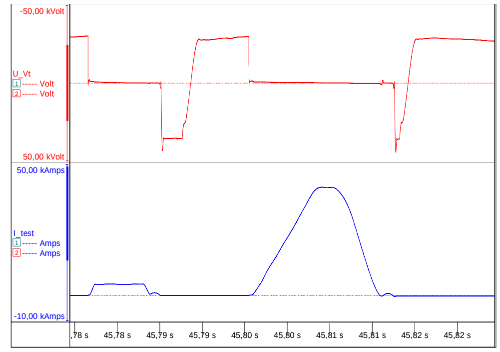

Figure 5 One-loop fault current with subsequent blocking voltage test

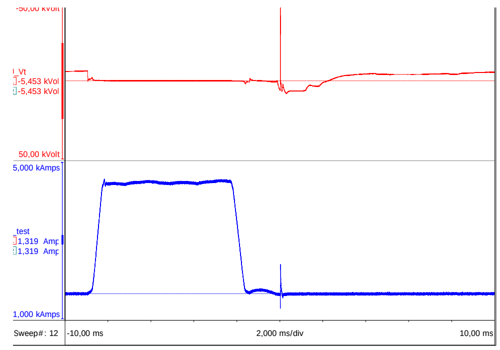

Figure 6 Tests with transient forward voltage during the recovery period

VI. Summaries

Converter valve design of Xiangjiaba – Shanghai ±800kV UHVDC transmission inherited all design merits used in modern HVDC thyristor valves. The use of 8.5kV 6" thyristors in the valve converts more power in an even compacted valve size.

Two 12-pulse converters are connected in series as one converter for 800kV pole voltage in this bulk power transmission project. Those two converters are installed in low voltage and high voltage halls respectively. Both converters use the same MVU design with two single valves assembled in one hanging support structure.

Comprehensive type test program was defined and followed to verify the valve and converter design. One single valve was dielectric and operational type tested. The MVU and MVU hanging structure in both HV valve and LV valve hall were dielectric type tested.

The type test results indicate that not one of single component was detected being short-circuited or degraded during and after the type test and the valve design is a success.

Because the test stresses used in the operational type test are generally greater than those that may meet in service the thyristor valves sustain a substantial margin in operation.

VII. References

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VIII. BIOGRAPHIES

Baoliang Sheng obtained his B.Sc degree from Xi'an Jiaotong University, China and his Ph.D. from Delft University of Technology, The Netherlands, in 1982 and 1995 respectively. From 1982 to 1992 he was a test and research engineer in XIHARI, China. He was a research engineer in KEMA, the Netherlands, and pursued his Ph.D. at Delft University of Technology from 1992 to 1996. He joined ABB Ludvika, Sweden in May 1996. He is Company Specialist in High Power Testing of Electrical Power Equipment and Senior Specialist in Design and Testing of HVDC Converter Valves and SVC Valves. He is Chairman of IEC TC115 Swedish subcommittee, convenor of IEC Strategic Group (SG2) on the standardization of ultra high voltage technologies, convenor of IEC SC22F WG15 on electrical testing of Voltage Sourced Converter (VSC) valves and member of several working groups in IEC SC22F and IEC TC33. He is Senior Member of IEEE.

Jonatan Dainelssion obtained his Master degree in electrical engineering from Uppsala University, Sweden in 2007. He joined ABB Power Systems, HVDC, Ludvika, Sweden in September 2007 as thyristor valve design and test engineer.

Yanny Fu graduated with her Master Degree from Xi'an Jiaotong University in 1985 in China and obtained her PhD degree from Technical University of Eindhoven in 1990 in The Netherlands. Since then, she has been working at KEMA and is a senior leading consultant at present. She is regular member Cigré SC B4 "HVDC and Power Electronics", chair of Dutch national Cigré committee NSC B4, convennor of Cigré working group B4-51 "Study of Converter Voltage Transients Imposed on the HVDC converter transformers", Dutch Member of IEC TC115 "HVDC systems above 100kV". Dr. Fu received the Cigré technical committee award in 2007 for her "remarkable contribution to the work of Cigré Study Committee B4: HVDC and Power Electronics".

Zehong Liu obtained his Master degree in electrical engineering from China Electrical Power Research Institute (CEPRI), China, in 1984. He jointed State Grid Corporation of China (SGCC) after graduation. He is deputy secretary of IEC TC115, convenor of IEC TC115 WG1 on the design of ground electrodes for HVDC links and active member in several Cigré and IEC working groups dealing with ultra high voltage power transmission. He is deputy director general of Ultra High Voltage Construction Department of SGCC.

Table 2 Operational test parameters per thyristor module

Test Duty	**Duration**	**I_{dc} (A)**	**I_{fault} (kA)**	**U_p (kV)**	**U_f (kV)**	**U_r (kV)**	**U_{imp} (kV)**
Heat-run test	60 min.	≥ 4200			≥ 22.1	≥ 22.1	
Max. temporary operating duty (α=90°) test	10 sec.	≥ 1400			≥ 27.9	≥ 27.9	
	2 sec.	≥ 1470		≥ 48.0			
Min. delay angle test 1	15 min.	≥ 4200				≤ 4.9	
Min. delay angle test 2	1 min.	≥ 4200				≤ 2.1	
Min. extinction angle test 1	15 min.	≥ 4200		≤ 6.5			
Min. extinction angle test 2	1 min.	≥ 4200		≤ 5.1			
Intermittent direct current tests	2 min.	< 400				≤ 4.9	
	10 sec.	< 400				≥ 33.3	
Tests with transient forward voltage during the recovery period		≥ 4200				≤ 6.5	≥ 50.0
One-loop fault current with re-applied forward voltage		≥ 4200	≥ 40.8		≥ 28.2		
Three-loop fault current without re-applied forward voltage		≥ 4200	≥ 41.7			≥ 17.0	
Continuous protective firing*	120 min.	≥ 4200			≥ 22.1	≥ 22.1	

U_p — recovery voltage peak, including over-shoot
U_r — power frequency recovery voltage peak in reverse direction
U_f — forward voltage prior to the firing instant
U_{imp} — forward transient voltage peak during recovery
* test on one thyristor module only