Reliability Assurance of HVDC Thyristor Valves by Rigorous Type Tests

Baoliang Sheng, *Senior Member, IEEE,* Roberto Rudervall, Hans-Ola Bjarme, Olaf Saksvik

***Abstract* — Rigorous type tests are essential to ensure the reliability of HVDC thyristor valves. A conventional six-pulse back-to-back direct test circuit is a proper representative of an actual network to test the valves. The test equivalence by this circuit has been proven by the reliable operations of valves installed worldwide.**

To keep pace with the fast development of power handling capability per single thyristor, an alternative test circuit, synthetic test circuit has been developed to continuously hold the stringent type test program of ABB's HVDC thyristor valves.

With properly defined test parameters, both the conventional six-pulse back-to-back direct test circuit and the synthetic test circuit can produce the stresses equal to or greater than the worst-case service stresses. As a result, higher reliability is exhibited by the tested valves.

***Index Terms* — HVDC thyristor valves, reliability, operational tests, six-pulse back-to-back test circuit, synthetic test circuit, high power laboratory**

I. Introduction

RELIBILTY and availability of HVDC thyristor valves are at the heart of HVDC power transmission. It is manufacture's responsibility to supply the well-proven HVDC thyristor valves to the utilities in order to make HVDC transmission a reliable means of electric power transport.

Laboratory tests are one essential method to verify the design and predicating the reliability of HVDC thyristor valves. The International Electrotechnical Commission (IEC) specified the test requirements in its international standard IEC60700-1 [1].

Laboratory type tests are classified into two categories, dielectric tests and operational tests. The dielectric tests are relatively simple since they only involve high voltage. The test facilities in most of the high voltage laboratories in the world can produce the test voltages as defined in IEC or in the user's specifications.

The operational tests are more complicated, due to the need to represent various operating modes of HVDC thyristor valves in service. All these operation modes involve not only a high voltage but also a high current as well. The laboratory operational tests, regardless of different operation modes, must be done under following conditions in order to represent the service stresses properly [2]:

- Same inlet coolant temperature as in service
- Same direct current
- Correct current deviate prior to the current zero crossing
- Correct rate of rise of recovery voltage and recovery voltage peak
- Same stray capacitance and voltage across it at firing instant

To verify the valve performance at various operation modes, a comprehensive test program has to be defined. As the basis for establishing sufficient confidence in the reliability of an HVDC thyristor valve the test program must at least include the following operational tests:

- Periodic firing / extinction test and protective firing test
- Maximum temporary operating duty test (α=90^{o})
- Minimum AC voltage tests (minimum firing voltage test and minimum extinction voltage test)
- Intermittent direct current test
- Tests with transient forward voltage during the recovery period
- One-loop fault current test with re-applied forward voltage and multi-loop fault current test without re-applied forward voltage.

Test circuits used in the early years were the three-pulse back-to-back test circuit, six-pulse back-to-back test circuit and alternative voltage test circuit. In these circuits, six-pulse back-to-back test circuit is concluded of the most representative of network due to the fact that the test circuit topology is the same as in service and the test circuit parameters are scaled directly from the network to the corresponding test section of a valve.

Modern HVDC thyristor valves have a high power rating with an even small number of thyristor levels in series connection. Testing these thyristor valves by using a conventional back-to-back test circuit comes up against the problem of few thyristor levels in series connection per test set-up, since all test laboratories face a common problem – limited power of the test installation. Testing a limited number of thyristor levels in series per valve function could cause uncertainty about the representation of voltage distribution over the thyristor levels during the test. To solve this problem either huge investment is needed to expand the testing power of a six-pulse back-to-back test circuit or a new testing method has to be developed.

Baoliang Sheng, Roberto Rudervall, Hans-Ola Bjarme and Olaf Saksvik are with ABB Utilities AB, Power Systems, Lyviksvägen 12, 77180 Ludvika, Sweden

(E-mail: baoliang.sheng@se.abb.com, roberto.rudervall@se.abb.com, hans-ola.bjarme@se.abb.com, olaf.saksvik@se.abb.com).

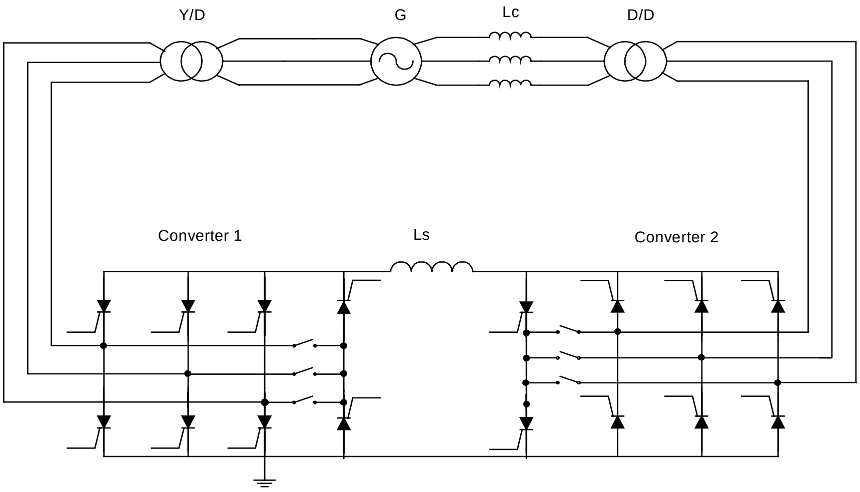

Fig. 1 A conventional six-pulse back-to-back direct test circuit

By analyzing the operations of HVDC thyristor valves in power systems, it can be seen that two distinct phases exist per power frequency cycle. After turn-on, the conduction of thyristors is characterized by a high current and a low voltage. After turn-off, the blocking of thyristors is characterized by the presence of high voltage only. Synthetic testing methods are based on the fact that the thyristor is stressed by high current and by high voltage at different times.

In a synthetic test circuit, the test current and voltage are fed by two or more power sources. By the help of auxiliary valves the test thyristors are connected to each source in turn at different intervals. The power request of each source can therefore be minimized.

Several synthetic test circuits have been developed [3][5]. These test circuit differ from each other in topology and most importantly in the test equivalence. This means that only test results acquired from a proper test circuit can ensure the valve performance.

II. A Conventional Six-Pulse back-to-back Test Circuit

Even starting from the first generation of HVDC thyristor valves ABB used a six-pulse back-to-back test circuit. This circuit comprises twelve valve branches as two three-phase bridge circuits with one bridge operating as a six-pulse rectifier and the other as a six-pulse inverter. This circuit is given in Fig. 1. Generators, Fig. 2, are used to feed these bridges, Fig. 3, and supply the test power.

A six-pulse back-to-back test circuit naturally produces voltage and current waveforms, which are very close to the ones in normal operation. Therefore, all the operational duties of an HVDC thyristor valve can be reproduced in this circuit. This circuit shows its superiority over others by a real-time interaction with valve control and convertor firing control system when the intermittent direct test current test is performed.

Due to the limited power installed in the test laboratories, testing the complete valve in a conventional six-pulse back-to-back direct test circuit or other circuits is unrealistic. A general method is to test one section of a valve per test set-up for more accurate test stress reproduction. Naturally, the test circuit parameters need to be scaled from the system to the corresponding test section [4][8].

To establish sufficient confidence in a section test, attention has to be paid on the voltage distribution of the valve. A higher safety margin on the maximum steady-state current and voltage is used in the section test in ABB in order to cover a possible uneven voltage distribution within the valve due to different recovery charges and the spread in voltage divider parameters. The current and voltage for the section test are:

$$I_{test} = 1.05 \cdot I_d \qquad (1)$$

$$U_{test} = 1.1 \cdot \frac{N_{test}}{N_{total}} \cdot U_d \qquad (2)$$

Where

I_d — Maximum steady-state current including overload

U_d — Maximum steady-state converter voltage

N_{test} — Number of thyristors under the section test

N_{total} — Number of thyristors per valve (excluding redundancy)

Fig.2 Two test generators in the high power laboratory

Fig.3 Six-pulse back-to-back test circuit

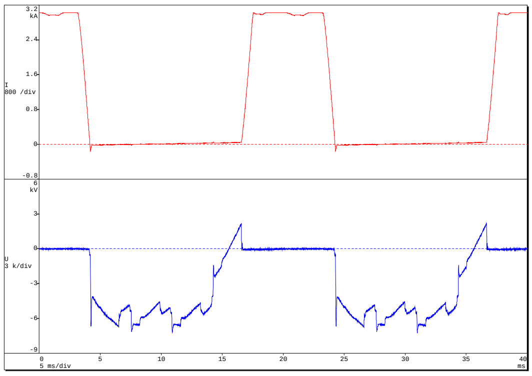

Fig. 4 Thyristor current and voltage in a six-pulse back-to-back direct test circuit

A typical test current and voltage waveform on the test object in the six-pulse back-to-back test circuit for the periodic firing and extinction test or heat-run test and protective firing test is shown in Fig. 4.

III. A Modern Synthetic Test Circuit

A new synthetic test circuit, Fig. 5, was successfully developed at ABB in Ludvika for the operational tests of modern thyristor valves in 2000 [5]. The motivation of this development is to acquire a proper test circuit that conforms to new IEC requirements for the testing of modern HVDC thyristor valve and for conducting the rigorous test program on ABB's products.

This synthetic circuit comprises a conventional six-pulse back-to-back circuit as the current source and a voltage oscillation circuit, Fig. 6, as the voltage source. The test object, together with the auxiliary valve V_{a1}, acts as one arm of the six-pulse bridge and conducts a DC current representative of the service current at the conduction period of the valve.

The voltage circuit is connected in by firing auxiliary valve V_{a3} in the commutation interval, which gives a prolonged commutation period as a result. The voltage circuit parameters are designed to be as same as the ones scaled from system to the test section. Proper average di/dt in the 200µs before current zero is therefore achieved. Close representation of thyristor / circuit interaction in the commutation interval and transient recovery interval is achieved as well.

A typical test current and voltage relationship on the test object in this synthetic test circuit for the periodic firing and extinction test is shown in Fig. 7. Compared with the test current and voltage in a six-pulse back-to-back test circuit shown in Fig. 4, the test circuit in this synthetic test circuit has a prolonged commutation time at turn-off due to the injection current of voltage circuit. This injection current produces extra thyristor conduction losses and yields total thyristor conduction losses slightly greater than those in service. Assured by the correct thyristor recovery charge by the close commutation current representation in the last 200µs of current aero, the thyristor turn-off losses would be the same.

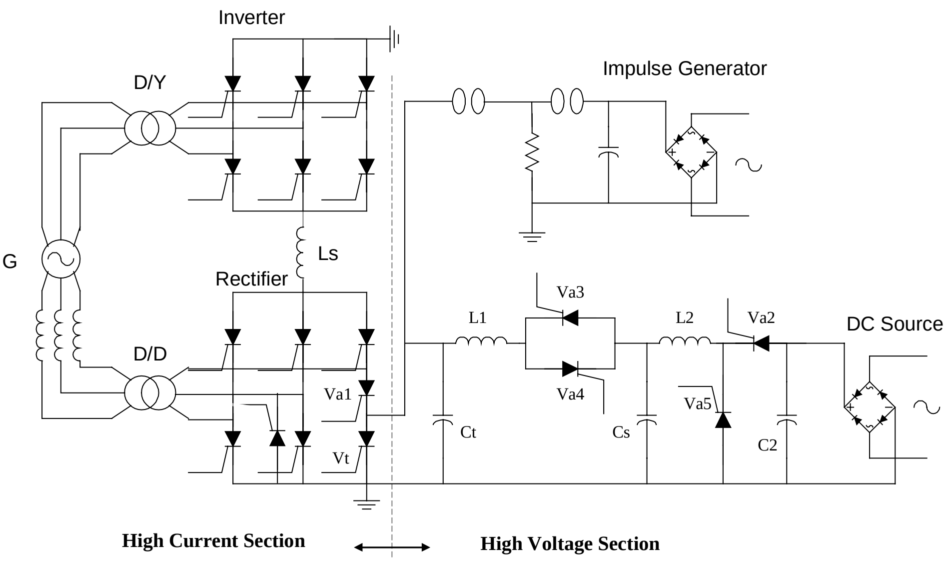

Fig. 5 A modern synthetic test circuit based on current injection method

Fig. 6 Capacitor banks in the voltage circuit

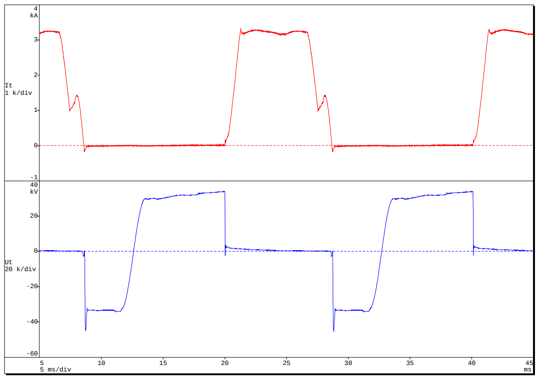

Fig. 7 Synthetic test circuit current and voltage in periodic and extinction test

In the recovery period, the recovery voltage differs from the service voltage. A remedy for this, which is used in the synthetic test circuit, is to study each test duty and assign the circuit parameters in order to produce a voltage stress no less than in service. For examples, when the periodic firing and extinction test is conducted, the test circuit will generate a reverse recovery voltage (including the transient recovery voltage) the same as in service but a higher forward voltage as shown in Fig. 7 and when $\alpha=90^{o}$ test is performed the test circuit must have a high test voltage level in order to compensate the absence of voltage jumps in the voltage waveform, which might otherwise decrease the snubber circuit losses.

IV. Rigorous Tests for HVDC Thyristor Valves by Using of the Synthetic Test Circuit

Using synthetic test circuits to test modern HVDC thyristor valves is an economical and technical necessary. ABB's synthetic test circuit inherits the close stress reproduction feature of a six-pulse back-to-back test circuit and offers extra flexibility by its ability to adjust the current stress and voltage stress independently. With up to maximum eighteen thyristors or three modules in series in one test set-up as the test object, the test could be considered to afford an adequate representation.

An advanced computer based system, MACH2 (Modular Advanced Control for HVDC), is used to control and protect the synthetic circuit. This system provides a full automatic

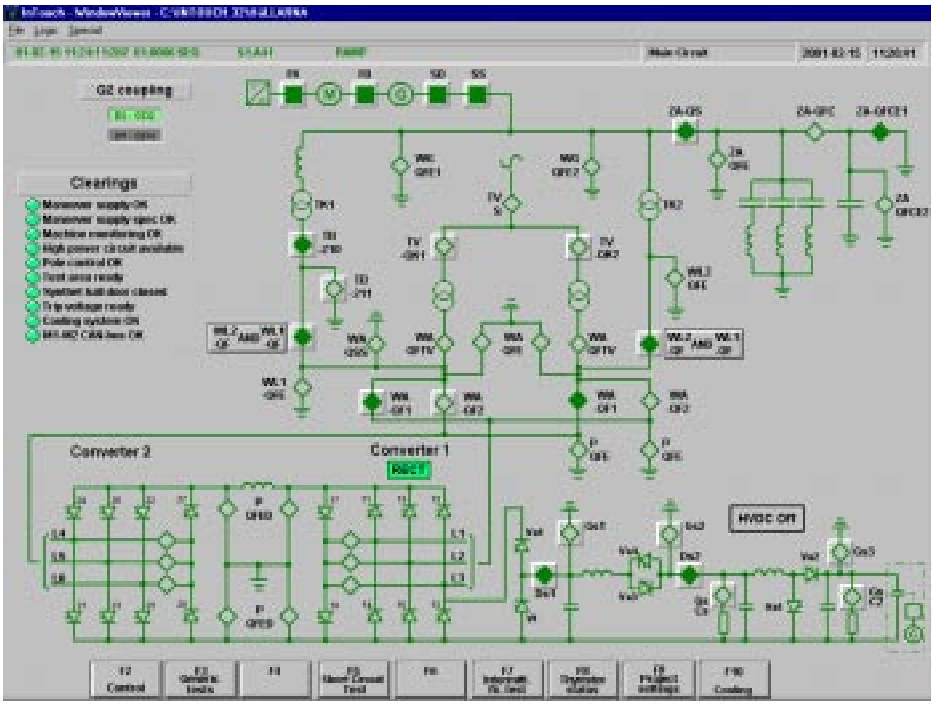

Fig. 8 Man-machine interface to execute various synthetic test duties

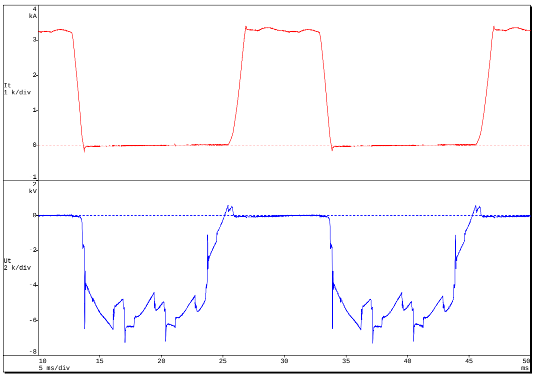

Fig. 9 Current and voltage in minimum delay angle test

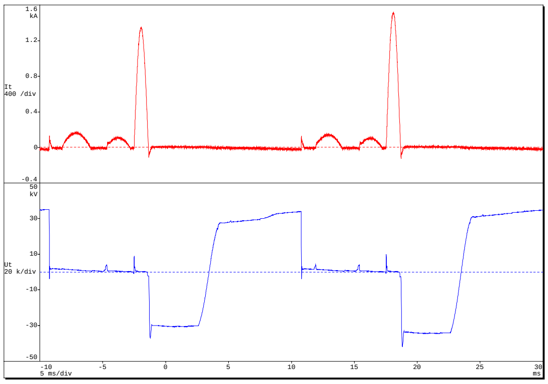

Fig. 12 Intermittent direct current test

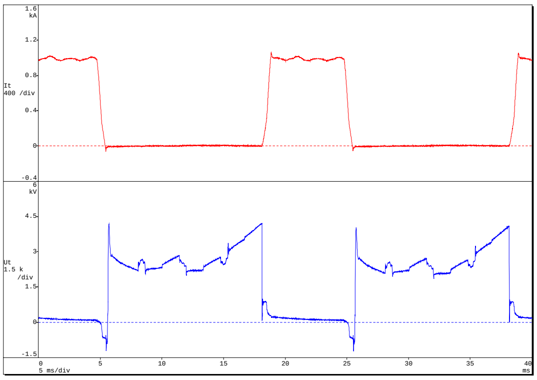

Fig. 10 Minimum extinction angle test

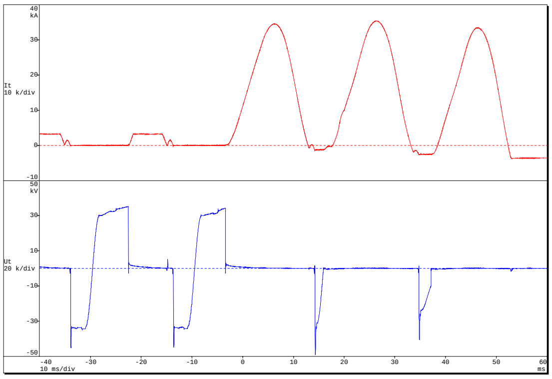

Fig. 13 Three-loop fault current without re-applied forward voltage

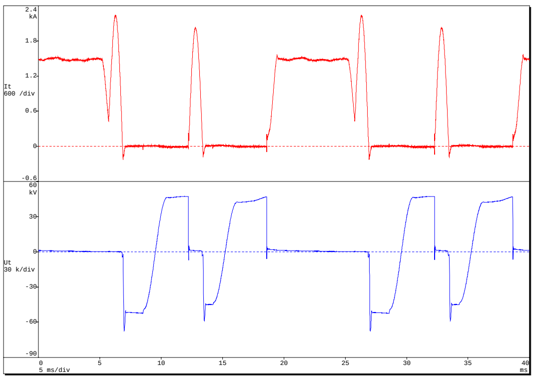

Fig.11 Maximum temporary operating test (α=90^o)

protection function and a user-friendly man-machine interface, Fig. 8, for easy access to the test circuit set-up before the test and the test parameter adjustment during the test.

When the periodic firing / extinction test and protective firing test are performed, Fig. 7, the maximum steady-state current is determined by Equation (1) and the maximum steady-state voltage is determined by the maximum commutation overshoot in each test duty and includes a test safety factor of 1.05 as specified in IEC.

Minimum AC voltage tests (minimum delay angle test and minimum extinction angle test) can be performed in the six-pulse back-to-back circuit, Fig. 9 and Fig. 10, for the driving voltage of this circuit is high enough to meet the test requirement.

While maximum temporary operating duty test (α=90^o) is performed, the voltage circuit is connected to the test object twice per cycle as shown in Fig. 11. The maximum steady-state test voltage is derived to a level that could reach the maximum service commutation overshoot and a same loss on the snubber circuit.

Tests with transient forward voltage during the recovery period are conducted with the impulse generator connected as shown in Fig. 5. The impulse generator can generate a transient voltage over a wide front time from 1µs to 100µs on the test object at any desired instant of thyristor recovery period.

The intermittent direct current test, the one-loop fault current test with re-applied forward voltage and the multi-loop fault current test without re-applied forward voltage are two test duties which are difficult for synthetic testing. However, difficulties have been overcome in this synthetic test circuit by the implantation of a conventional six-pulse back-to-back circuit as the current source and the use of current injection method to couple the voltage circuit in. As shown in Fig. 12 the multi-gate-pulse releasing strategy has been properly proven in this circuit under intermittent direct current testing. Fig. 13 showed another stringent test that this synthetic test circuit offers, the multi-loop fault current test without re-applied forward voltage. Just as in service, no transit time exists from normal periodic firing and extinction to short-circuit fault in the fault current tests of valve.

V. SUMMARY

Laboratory tests are a reliable means to judge the reliability and availability of HVDC thyristor valves while a rigorous type test program is followed in a proper test circuit. Starting from the first generation of HVDC thyristor valves, ABB used a six-pulse back-to-back test circuit to conduct the operational tests of valves. Analysis reveals this test circuit gives the closest representation of network stresses on the test object. A high safety margin must be added to the maximum steady-state values to cover possible uneven voltage distribution caused by the different recovery charges of thyristors and the spread in voltage divider parameters under a section test of the valve. The validity of this six-pulse back-to-back test circuit and the philosophy behind the design of the test parameters have been proven by the reliable operation of tested valves installed worldwide.

The high power rating of modern HVDC thyristor valves and modified test requirements in IEC60700-1 result in the conventional six-pulse back-to-back test circuit not preferable, mainly because of the high test power requirement and lack of test circuit adjustment flexibility.

As an alternative, synthetic testing offers a better solution. The use of more than one power source to supply the test current and voltage in a synthetic test circuit requires a throughout study on the way to connect these sources together.

Three parameters are important when conducting stringent tests by using a synthetic test circuit. They are: conduction losses of the test thyristors, recovery charge of the thyristors and amplitude of the commutation voltage overshoot. A synthetic test circuit based on the current injection method fulfills the rigorous test requests. This synthetic test circuit has been used to verify the HVDC thyristor valves for Three-Gorges — Changzhou HVDC Transmission Project [6] and GARABI II HVDC Back-to-Back Project [7]. Since the test stresses are equal to or greater than the worst-case service stresses, the test valves exhibit higher availability and reliability.

VI. REFERENCES

[1] *Thyristor valves for high voltage direct current (HVDC) power transmission - Part 1: Electrical testing*, IEC60700-1 (1998-09)

[2] Task Force 01 of Working Group 14.01, "Voltage and current stresses on HVDC valves, " ELECTRA No.125, July 1989

[3] Task Force 03 of Working Group 14.01, "Test Circuits for HVDC Thyristor Valves," CIGRE Technical Brochure 113

[4] Åke Ekström and Lars-Erik Juhlin, "Testing of Thyristor Valves" Cigré paper 14-03 presented at the Session 1972

[5] B.L. Sheng, E. Jansson, A. Blomberg, H-O. Bjarme and D. Windmar, "A New Synthetic Test Circuit for the Operational Tests of HVDC Thyristor Valves," in *Proc. IEEE 16th APEC 2001 conf.*, pp.1242 – 1246

[6] Baoliang Sheng, Hans-Ola. Bjarme, Pierre Riffon and Weimin Ma, "Operational Tests of the Three-Gorges — Changzhou HVDC Thyristor Valves by Using a Synthetic Test Circuit" in *Proc. Cigré ICPS'2001 Conf. on Sep.03-05, 2001, Wuhan, China*, pp.396 – 400

[7] Baoliang Sheng, "Operational Tests of Garabi II HVDC Thyristor Valves" in *Proc. IEEE PES 2002 T&D Latin America Conf. on Mar.18-22, 2002, São Paulo, Brazil*

[8] J.C. Gledow, N.L. Diseko and R. Rudervall, "Design and testing of thyristor valves for the New Zealand DC project," Paper No. 2.1, published at the International Colloquium on HVDC & FACTS in Wellington, New Zealand, September 1993

VII. 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 to 1992 he worked at National High Power Laboratory, XIHARI, China, as a test and research engineer. He worked at KEMA, the Netherlands, as a research engineer and towards his Ph.D. at Delft University of Technology from 1992 to 1996. He joined the High Power Laboratory of ABB Switchgear AB, Sweden, in May 1996. Since September 2000 he has been with ABB Utilities AB, Power Systems, as a development engineer. He was appointed as Company Specialist in the area of High Power Testing of Electrical Power Equipment in 1999. His special fields of interest include study of transient phenomena in power systems, laboratory reproduction of network switching conditions, synthetic testing of HVAC and HVDC circuit breakers, development of HVDC thyristor and SVC valves, direct and synthetic operational tests of HVDC thyristor valves and SVC valves.

Roberto Rudervall was born in Tandil, Argentina in 1957. He obtained his Master's degree from Universidad Nacional de Mar del Plata in 1986. He joined ABB in 1988 and worked in electrical design and testing of HVDC thyristor valves until 1994. He was a member of the TF03 Cigrè WG 14.01 and member of the WG06 of IEC SC21. From 1994 to 1997 he was Main Circuit Design manager and from 1997 Manager of Marketing HVDC & HVDC Light at ABB Utilities.

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 Utilities AB, Power Systems, as the manager of Thyristor Valve Electrical Design Department. He is member of IEC working group IEC 22F MT9.

Olaf Saksvik was born in Lökken, Norway in 1962. He received his M.Sc. degree in materials engineering from the Norwegian Institute of Technology, Trondheim, Norway in 1989. In 1990 he joined ABB Power Systems (now ABB Utilities), working with design and development of Converter Valves. From 1996 to 1999 he was responsible for the mechanical design of converter valves. In 1999 he became manager of the Converter Valve Department at ABB Utilities.