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HIGH VOLTAGE DC SYSTEMS AND THE RELATED COMMISIONING

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Abstract- The number of High Voltage Direct Current (HVDC) projects worldwide has increased considerably due to the growing interest in this mature technology. Rapid development in semiconductor technology have led to the development of converter technology and thus new application areas have emerged. In this study, historical development of HVDC systems, differences among them considering installation types and application areas are explained. Circuit models of HVDC systems, working principle and general usage purposes are also explained. The differences between conventional Current Source Converters (CSC) and Voltage Source Converters (VSC), which are expressed as relatively new technology, are discussed. Also, within the scope of a project, a HVDC prototype system developed by local engineers from mechanical design to control and protection software has been described. In addition, the tests to be performed before commissioning of HVDC and similar systems are explained. Descriptions of the tests, methods to perform the tests and some issues that should be considered while performing the tests are given.

Keywords: HVDC, CSC, VSC, MMC, Insulation Tests.

1. INTRODUCTION

The demand for power is increasing day by day, and this reveals the necessity of developing the power system. The development of power systems is possible with the development of power generation and transmission systems. HVDC transmission systems are one of the most reliable ways to transfer power [1].

Comparison of costs of HVDC and HVAC transmission systems is given in Figure 1. As can be seen from the figure the installation cost of the converter stations required for DC transmission is considerably higher than the installation cost of the transformer substations required for AC transmission. But when the transmission distance exceeds a certain limit (break-even distance), the direct current (DC) transmission cost becomes cheaper than that for AC. At the same time, it is also a great advantage that there is no frequency parameter in the DC transmission that makes the AC transmission control more complicated [2-4].

The break-even distance is approximately 500 to 800 km for an overhead line. However, this limit may vary depending on country-specific cost factors [5, 6]. It can be seen from the Figure 1 that the losses in DC transmission are less than the losses in AC transmission.

In addition to economic reasons, HVDC systems can also be preferred when there is sea between transmission points, when it is necessary to connect networks with different frequencies, for political or strategic reasons or for other reasons described later in this document. HVDC systems to be connected to the network are complex structures formed by the combination of many equipment and it is inevitable to perform some function and reliability tests before commissioning such systems. In this study, after HVDC systems are explained in detail, the features of the locally designed HVDC prototype system are explained. Insulation tests planned on the prototype system are given with details and information about the commissioning of these systems is given.

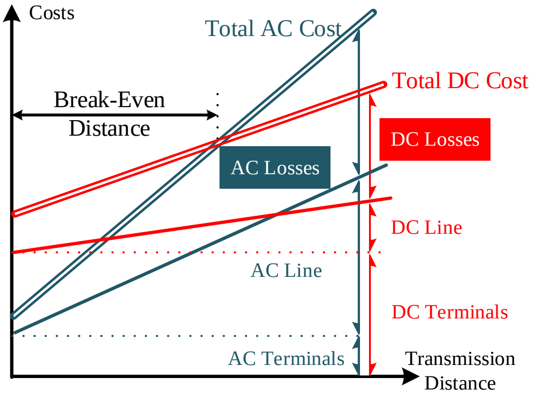

Figure 1. HVDC and HVAC transmission system cost [5]

2. HVDC SYSTEMS

HVDC systems are preferred for power transmission over long distances because the overall cost of AC transmission is more expensive. In addition, DC transmission becomes advantageous when evaluated in terms of losses [5].

Some advantages of HVDC systems are more power can be carried per conductor, line construction is simpler than AC, there is no skin effect on cables, synchronization is not required when connecting to the network, distance is not limited by stability. However, disadvantages of HVDC systems can be summarized as they are expensive and complex. Figure 2 shows example applications of HVDC transmission systems.

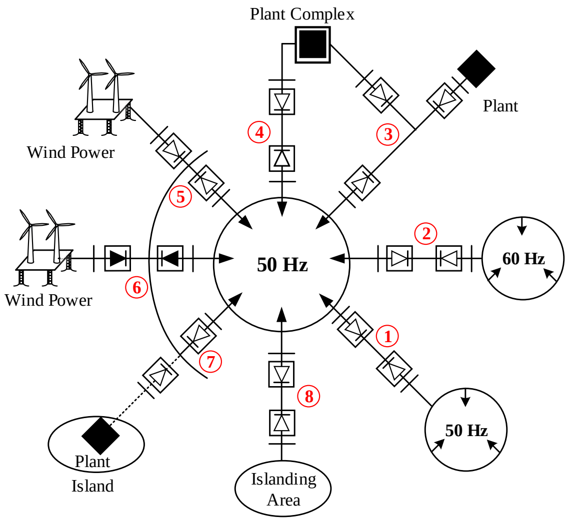

Figure 2. Various applications of an HVDC system [5]

The HVDC system given in Figure 2 are described below considering the given numbers;

1- Power transmission via long-distance overhead line.

2- Since there is no frequency or phase angle restriction between two AC networks for the connection of the HVDC system, it can be used as back-to-back when connecting networks with different frequency values.

3- While it is necessary to transfer power from a remote point, HVDC systems can be used when more than one country need to provide transmission over the same DC line for strategic or political reasons.

4- Since reactive power is not transmitted through a DC link, two AC systems can be connected over an HVDC connection without increasing short circuit power. This technique can be useful in generator connections.

5- HVDC transmission systems can be used when wind power plants are in a remote location from the consumer.

6- Unlike conventional thyristor-based HVDC systems, Pulse Width Modulation (PWM) can be used in HVDC systems consisting of IGBT-based VSCs. This technology is very suitable for wind energy connection to the grid.

7- Power transmission of bulk energy through sea cable.

8- Fast and precise control of the flow of energy over an HVDC link to create a positive damping of electromechanical oscillations and enhance the stability of the network by modulation of the transmission power by using a back-to-back HVDC Systems [5].

HVDC systems can be divided into two groups according to the application. In one of these groups the rectifiers and inverters used in HVDC system are in the same station without using transmission line, these are called as HVDC back-to-back systems which is shown in Figure 3.

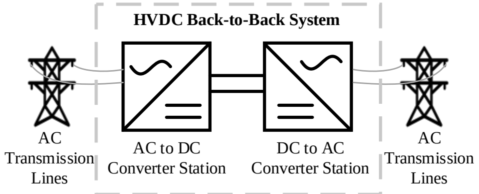

Figure 3. HVDC back-to-back system

In the second group the rectifiers and inverters used in HVDC system are in different locations, connected through transmission lines, these are called as HVDC transmission systems which is shown in Figure 4.

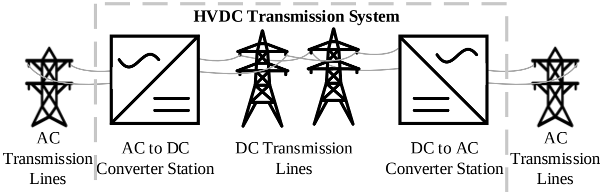

Figure 4. HVDC transmission system

Conventional HVDC systems are based online commutated current source converter in which thyristors are used as semiconductors. With the developing semiconductor technology, self-commutated voltage source converters have been developed and these converters have been used instead of line commutated current source transducers in HVDC systems.

2.1. Line Commutated Current Source Converters

LCC HVDC using mercury arc valves was introduced at USSR in 1950 and 1954 in Sweden. The first application of thyristor valves was made in Canada in 1972 [7].

Since the 1960s, it has become very reliable due to the successful use of thyristor-based line commutated converters (LCC) in flexible AC transmission (FACT) or HVDC systems [8]. A line-commutated current source converter is shown in Figure 5.

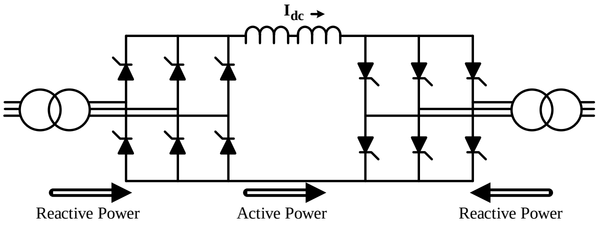

Figure 5. Line-commutated current source converter system [5]

A suitable number of thyristors are connected in series to reach the desired DC output voltage. Three-phase full-wave controlled bridge rectifiers, also called as 6-pulse rectifiers, form the basis of these converters. The 6-pulse bridge rectifier is consisting of 6 controllable switching elements or thyristor valves. In one period, a total of 6 commutations or switching operations take place, resulting in harmonics contents of the output DC voltage and in the input AC current of the rectifier [9]. Therefore, there are needed for suitable filter design to eliminate the generated harmonics [7].

The average output voltage and power flow can be adjusted by controlling the commutation angle of switches. In these converters the power flow direction will change when the voltage polarity is reversed [7].

Line commutated converters needs strong AC voltage sources capability. The three-phase symmetrical short circuit capacity of the AC grid at the point where the converter is connected must be at least twice the power of the converter. The ratio of three-phase symmetrical short circuit capacity of ac mains to converter power is called the "short circuit ratio (SCR)" and the operation of systems where this ratio is less than two is only possible when AC voltage is controlled quite rapidly and continuously [10].

Line commutated Current Source Converters can only operate under lagging operation condition, so the conversion process requires reactive power. Reactive power is supplied from the ac filters, shunt or series banks capacitors that are an integral part of converter station. [9].

2.2. Self-Commutated Voltage Source Converters

Using two-level and three-level VSC, the VSC HVDC transmission system was first introduced in the late 1990s [7]. The rapid development in semiconductor technology has made the use of Insulated Gate Bipolar Transistor (IGBT) based VSCs more attractive in HVDC transmission.

The VSC can be operated as either an inverter or as a rectifier. Similarly, the VSC can be operated either capacitively, injecting reactive power into the AC network, or inductively, absorbing reactive power from the AC network [11].

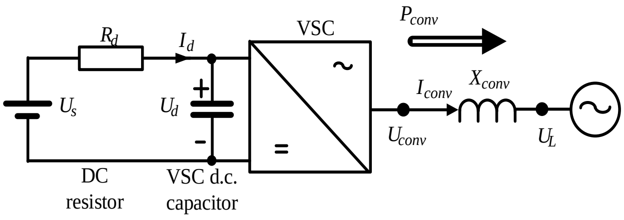

Figure 6. Diagram of generic voltage source converter [11]

On the AC side, there is an interface inductance that serves two purposes. It stabilizes the AC current and controls the active and reactive output power from VSC. The interface inductance can be implemented as reactors, as leakage inductances in transformers, or as a combination of these two. The DC capacitor on the input side and the AC interface inductance on the output side are important components for the proper functioning of a VSC [11].

By changing the amplitude of the VSC output voltage and the phase angle between the AC grid and VSC output voltage, the active and reactive power exchange between the AC grid and VSC is controlled [11].

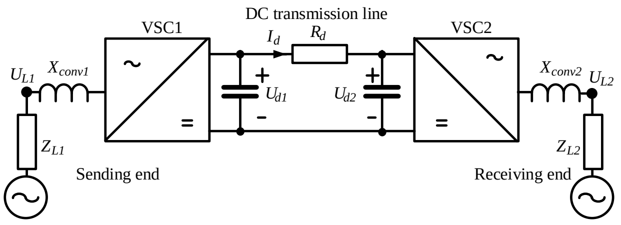

Figure 7. VSC transmission scheme [11]

In the VSC transmission scheme (Figure 7); there are two different VSCs connected to different AC mains and on the DC side these VSC systems are connected to each other via a DC transmission line. One of the basic characteristics of VSC is that the DC voltage polarity is always the same (in contrast with LCC HVDC, where the polarity of DC voltage depends on the direction of power transfer). In Figure 7, the current flow and the power flow are from VSC1, the sending or rectifier end to VSC2, the receiving or inverter end [11].

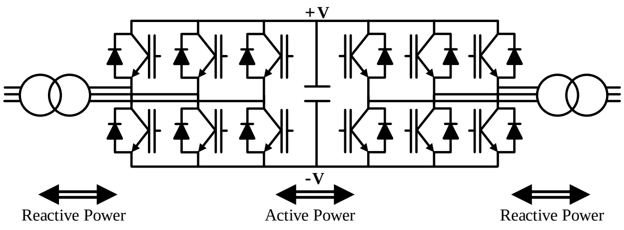

Figure 8. Self-commutated voltage source converter system [5]

VSC HVDC (Figure 8) technology provides significant technical and economic advantages over conventional HVDC systems [12]. Some important advantages of VSC HVDC compared to CSC HVDC are as follows; since there is no need for harmonic filters the installation areas are about half of CSC systems, there is no need for higher short circuit capability like CSCs for operation, active power control is bi-directional, active and reactive power can be controlled independently, IGBT is used instead of thyristor, black-start is possible without additional equipment. VSC topologies used in HVDC systems can be classified as two and multi-level.

2.2.1. Two Level Converters

In two level converters, a high number of switching elements are connected in series to achieve the desired voltage level. The two-level voltage source converter structure is given in Figure 9 and the output voltage waveform of this converter is given in Figure 10.

Two-level converters can be preferred because they are more economical than multilevel convertors. However, if two-level converters are used, passive AC filters are needed to suppress harmonics that disrupt the grid and in addition, high switching frequency is required to reduce the size of AC passive filters [13].

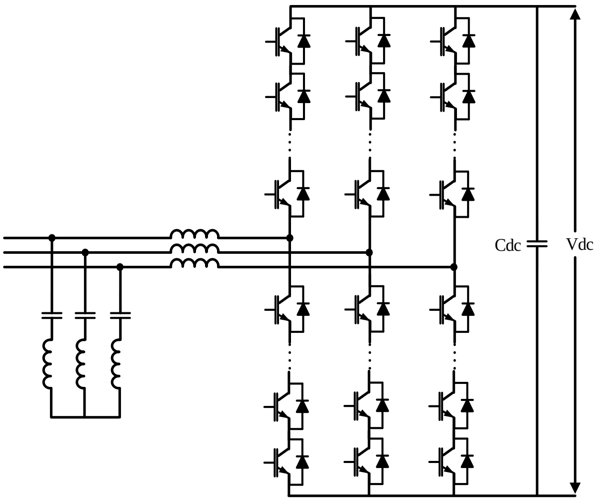

Figure 9. Two level converter topology [13]

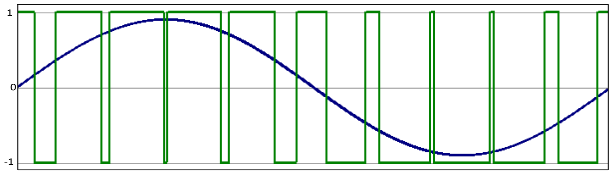

Figure 10. Two level PWM strategy

Arm currents with high *di*/*dt* cause unwanted overvoltages on IGBTs or high voltage *dv*/*dt* due to switching voltage in each arm of the converter causes electromagnetic interference with the control system. These limitations cause some restrictions in the design of these converters [13].

2.2.2. Modular Multilevel Converters

Modular multilevel converters (MMC) must be carefully designed, especially in terms of losses, because of their complex topology structures and the large number of sub-modules. However, in terms of voltage-source converter high voltage direct current (VSC HVDC) systems, MMC is preferred due to its higher efficiency [14].

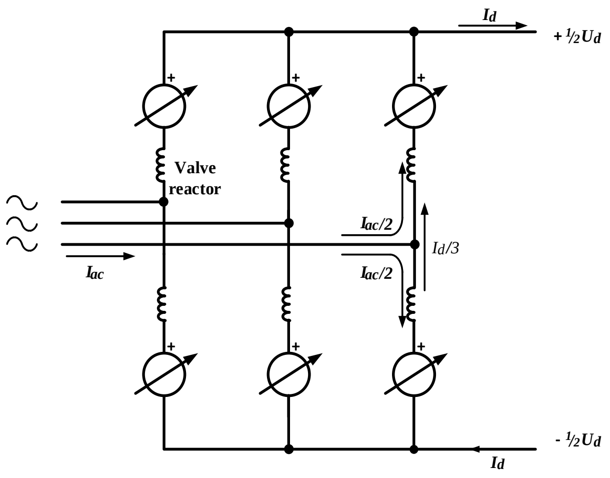

Figure 11. Electrical equivalent for a converter with VSC valves acting like a controllable voltage source [11]

As can be seen in Figure 11, each of the valves can be referred to as a controllable voltage source in MMC. Also, each VSC level includes power semiconductors and a capacitor for energy storage.

Each of 6 variable voltage sources shown in Figure 11 is realized with a series connection of identical VSC valve levels with an electrical equivalent as shown in Figure 12.

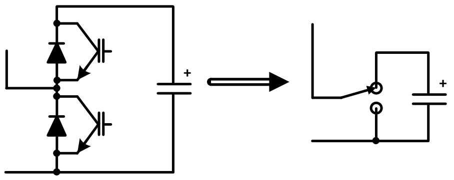

Figure 12. VSC valve level arrangement and equivalent circuit in MMC topology in half-bridge topology [11]

The VSC valve level is a two-terminal component with its own DC storage capacitor unit as shown in Figure 12. These VSC valve levels are individually controlled and can be switched between a state with full voltage (voltage of the associated storage capacitor) and a state with zero voltage for both current directions. If the voltage is applied to the VSC valve level terminals, the capacitor can be charged and discharged dependent on the current direction of the converter phase arm [11]. The electrical arrangement of VSC valve levels and valve reactors in a converter block is shown in Figure 19.

The three-level voltage source converter output voltage waveform is given in Figure 13 and multilevel is given in Figure 14.

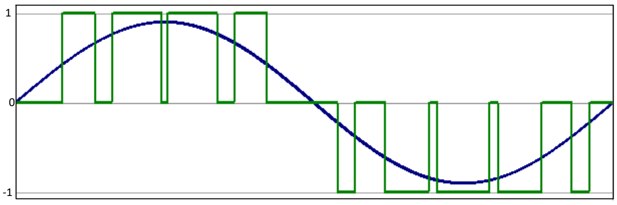

Figure 13. Three level PWM strategy

Multi-level converters have advantages as, the switching losses of the switches are low, and the output voltage waveform of converter is very near to a sinusoidal [15] wave which removes the need for a harmonic filter [16].

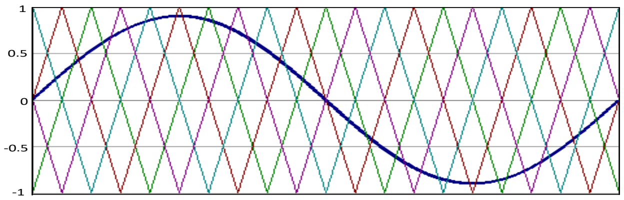

Figure 14. Multi-level PWM strategy

3. HVDC PROTOTYPE SYSTEM

In the literature, three main topologies have been proposed for the submodules of MMC. These are half bridge, full bridge and double clamped submodules. Apart from these, hybrid sub-module circuit topologies are three level flying capacitor, three level neutral-point-clamped and five level crosses connected [17]. In this study, hybrid topologies are not addressed.

Half-bridge submodules comprise two semiconductor switches, antiparallel diodes to them and a DC storage capacitor. The output of the half bridge submodules given in Figure 15 is equal to the capacitor voltage or zero according to the switching state [18].

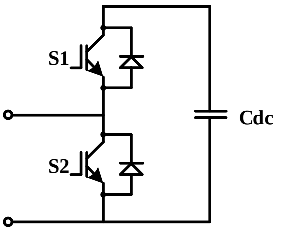

Figure 15. Half-bridge submodule [18]

The full bridge submodule shown in the Figure 16 consists of four semiconductor switches, antiparallel diodes to them, and DC storage capacitors. This topology allows positive and negative DC capacitor voltage to be seen at the lower module output. There is no need for negative voltage condition in normal operation. This situation is effective in a short circuit that will occur in the DC bus [18].

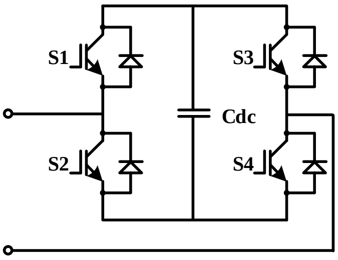

Figure 16. Full-bridge submodule [18]

The clamp double submodule is composed of two equal half bridge circuits (Figure 17). In this topology, the half bridges are connected so that the positive terminal of one-half bridge is connected to negative terminal of the another one [19]. The operation of the upper and lower half bridges is similar; therefore, it is sufficient to consider only one-half bridge in loss calculations [18].

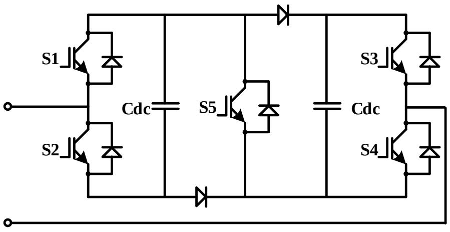

Figure 17. Clamp double submodule [18]

Table 1. Comparison of submodule topologies [17]

SM Topology	DC Fault	Losses
Half bridge	No	Low
Full bridge	Yes	High
Clamp double	Yes	Moderate

As it is shown in Table 1, the most advantageous topology in terms of losses is the half bridge submodule topology. This is because the number of switching elements of the half-bridge submodule is less than the others. When evaluated in terms of DC fault, the most disadvantageous topology is the half bridge submodule. However, in HVDC systems with back-to-back structure, unlike transmission type HVDC systems, there is a DC bus indoors instead of the external DC line. Since the possibility of DC faults is very low, the disadvantage in this regard is ignored, and the half bridge submodule is preferred in the HVDC Prototype system designed.

Within the scope of the project, whose main motivation is the development of the 100 MVA, HVDC system that provides interconnection between our country and a neighbor country, firstly a HVDC system prototype was produced. The prototype system is a self-commutated modular multilevel converter based, back-to-back HVDC, 9 MVA and is normally designed to operate at a voltage of 34.5 kV. However, all performance tests of the system have been carried out at 5.5 kV voltage level in order to work on the safe area.

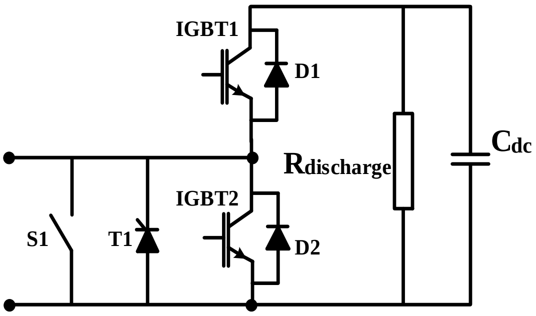

Figure 18. Half-bridge submodule of prototype system

The prototype system consists of 84 sub-modules, 21 sub-modules in each arm. It is consisting of 7 sub-modules per phase in each arm that are aligned from top to bottom in A, B and C phases and a multi-story structure is constructed (Figure 20).

The sub-modules are designed as half-bridge rectifiers (Figure 18) and connected in series using copper busbars (Figure 20).

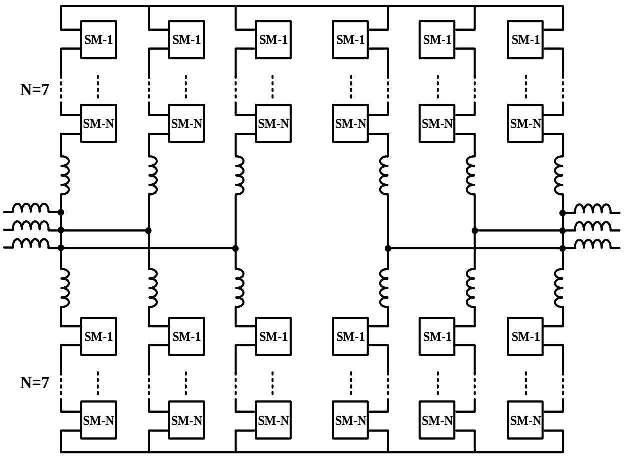

Figure 19. HVDC prototype system scheme

4. COMMISSIONING AND INSULATION TESTS

During commissioning of the HVDC system, HVDC equipment is verified in groups and in conjunction with the control & protection (C&P) systems. Dynamic Performance Study (DPS) must be completed before testing and simulation results are used as a reference when doing tests. DPS studies often provide information on how the HVDC system will behave and its effects on the AC grid in various operating scenarios or fault situations. Usually, commissioning process can be divided into 4 major parts [20].

Factory Tests includes the functionality and verification of connections of the control and protection equipment of the system. These tests are performed at the supplier's factory before the equipment is sent to the site [20].

Pre-Commissioning Tests includes simple functional tests of all electrical or mechanical system equipment. Subsystem Tests includes individual tests of subsystem groups that complete the main system. Tests under this heading verify the interconnection and functionality of all equipment of the subsystems [20].

System Tests includes energizing the system and testing all its functions when energized, such as controlling active and reactive power transmission. The precondition to this subsystem test is that all cabling installation, termination and insulation testing have been completed. Insulation tests are concerned with the verification of the mechanical design of the system and the correct functioning of the equipment under operating conditions [20].

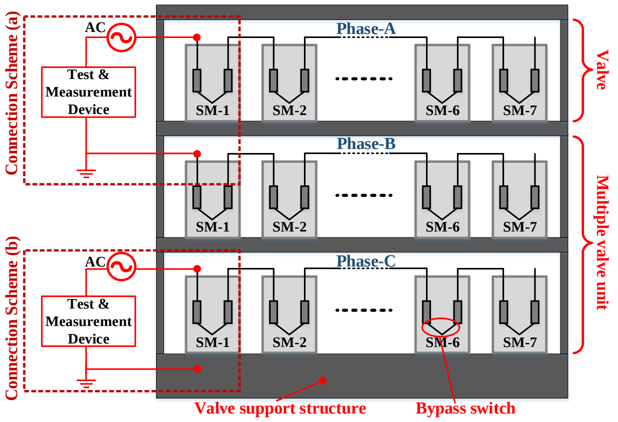

Figure 20. Submodules and valve of prototype system

In this study, AC insulation tests planned for HVDC system prototype based on [21] are explained. Performing methods of these tests and methods of calculating test voltages are explained.

The AC insulation tests mentioned in the standard are divided into two in terms of the connection scheme of the test equipment. One of these connection schemes is between phase-to-phase (Figure 20 - connection scheme, a) and it is called dielectric tests on multiple valve unit. The other one is between phase-to-ground (Figure 20 - connection scheme, b) and it is called dielectric tests on valve support structure.

4.1. Lightning Impulse Tests

A standard high voltage impulse generator (Figure 21) and measurement system should be used for lightning impulse tests.

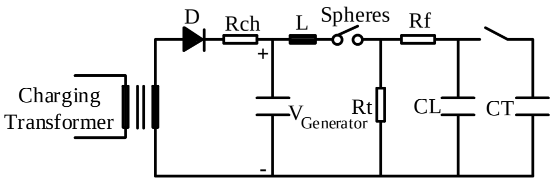

Figure 21. High voltage impulse generator circuit

The purpose of this test is to check the reliability of the material used against the lightning impulse signal. A standard lightning impulse voltage wave shape in accordance with [22] is shown in Figure 22.

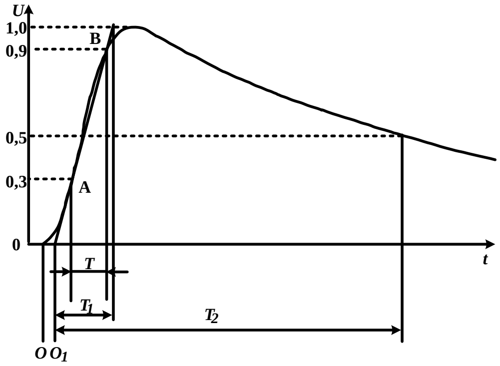

Figure 22. Lightning impulse voltage time parameters [22]

According to Figure 22, Front Time, T_1 is;

$$T_1 = 1.67(t_{90} - t_{30}) \quad (1)$$

Time to half value, T_2 is;

$$T_2 = (t_{50} - t_0) \quad (2)$$

where virtual zero, t_0 is;

$$t_0 = (t_{30} - 0.3T_1) \quad (3)$$

Virtual origin, O_1 is instant preceding that corresponding to point A, of the test voltage curve (Figure 22) by a time $0.3T_1$.

The standard lightning-impulse voltage is described as a 1.2µs (front time) - 50µs (time to half-value) [23]. The passing criteria for lightning impulse tests are given in Table 2. If the test results are within the range given above, the test has been successful.

Table 2. Lightning impulse test passing criteria

Parameter	Passing criteria
Test voltage	± 3%
Front Time	± 30%
Time to Half Value	± 20%

4.1.1. Valve Support Lightning Impulse Test

The purpose of this test is to check the reliability of the material carrying the sub-modules against the lightning impulse signal. Metal holders or insulators are used as valve support structure in most HVDC designs on the market.

But the material used in this design is FR-4, which is both an insulating and a non-combustible material. Valve support lightning impulse test comprises of three applications of positive polarity and three applications of negative polarity lightning impulse voltages between the main terminals of the valve (connected together) and earth (Figure 20 - Connection scheme, b) [21]. The test voltage is selected in accordance with the Standard insulation levels for range I (1 kV < $U_m \leq$ 245 kV) of [24]. For 36 kV voltage level Standard rated lightning impulse withstand voltage peak value is 170 kV.

4.1.2. Multiple Valve Unit Lightning Impulse Test

The purpose of this test is to see if there is any electrical breakdown after a lightning impulse is applied between the sub-module phases. In these tests, three positive and negative lightning impulse must be applied between one end of the sub-modules of one short-circuited phase and one end of the sub-modules of another short-circuited phase (Figure 20 - Connection scheme, a). MVU lightning impulse voltage, U_{tlm} is determined in accordance with the following rule [21]:

$$U_{tlm} = \pm LIPL_m \cdot k_8 \cdot k_t \tag{4}$$

4.2. AC Voltage Tests

The purpose of the AC voltage tests is to verify that the partial discharge starting and ending voltage values are above the maximum operating voltage values that can be seen on the equipment. In this context; voltage values higher than the rated operating voltage are applied to the system for a long time. Subsequently, it is monitored whether there is any electrical breakdown.

The high voltage AC test device combined with a partial discharge measurement device should be used for AC voltage tests.

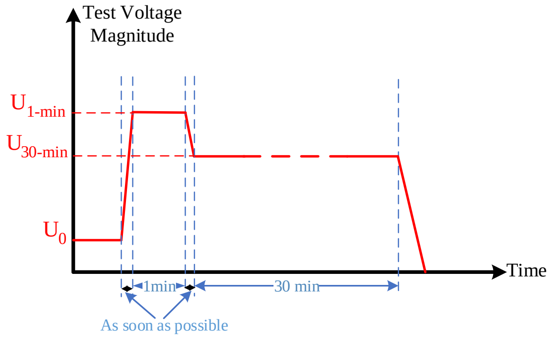

Figure 23. AC Voltage test voltages and related durations

Test durations and values are shown in the Figure 23. In the first stage of the test, a value of not more than 50% of the maximum test voltage should be applied. Then, starting from the initial voltage value, it should be increased as quickly as possible to 1-min test voltage calculated according to Equation (5) and (7). After remaining at this value for a period of 1 minute, it should be reduced as quickly as possible to 30-min test voltage calculated according to Equations (6) and (8). It must be kept constant at this value for 30 minute and then reduced to zero.

Before the end of the 30-min test the level of partial discharge must be monitored and recorded over a 1 minute period. According to the standard if the value of partial discharge is below 200 pC, the design may be accepted unconditionally, otherwise the insulation level of the test system should be re-evaluated [21].

4.2.1 Valve Support AC Voltage Test

To perform the test, the AC test voltage must be applied between the main terminals of the valve (connected together) and earth (Figure 20 - Connection scheme, b). The RMS value of the valve support AC test voltage, U_{tas} is determined in accordance with the following equations:

$$U_{tas-1\min} = \frac{U_{mS1}}{\sqrt{2}} \cdot k_4 \cdot k_t \tag{5}$$

$$U_{tas-30\min} = \frac{U_{mS2}}{\sqrt{2}} \cdot k_4 \tag{6}$$

4.2.2 Multiple Valve Unit AC Voltage Test

The AC test voltage must be applied between two series connected sub-modules (valve) of any two different phases (Figure 20 - Connection scheme, a). The RMS value of the multiple valve unit AC test voltage, U_{tam} is determined in accordance with the following equations:

$$U_{tam-1\min} = \frac{U_{mm1}}{\sqrt{2}} \cdot k_6 \cdot k_t \tag{7}$$

$$U_{tam-30\min} = \frac{U_{mm2}}{\sqrt{2}} \cdot k_6 \tag{8}$$

5. CONCLUSIONS

The main requirement for the selection of HVDC system is generally economic concerns. However, there may be other reasons for its preference; direct connection of two asynchronous electrical networks operating with different frequencies. This is feasible only with HVDC systems. In addition, the short circuit current level in HVDC systems is lower than that for HVAC systems. For long underground lines also HVDC systems are preferred. Besides, HVDC systems can be preferred as an economical solution for offshore wind farm connections.

The development of IGBT technology has also provided new possibilities (VSC HVDC) for HVDC applications. Although the advantages of VSC HVDCs compared to CSC HVDCs are explained in this study, the ratings of VSC HVDCs are still relatively low compared to CSC HVDCs. Because LCC technology has been on the market for a longer time so as it is known and reliable. However, it can be expected that usage ratings might increase as the VSC HVDC technology develops further.

In addition to these, it is extremely important that some tests must be completed before commissioning the HVDC or similar FACT systems to be connected to the electricity transmission or distribution system. Dynamic performance study and factory tests must be completed before the system is energized.

Also, insulation tests being one of the most important of these tests should be done carefully by experts. Insulation tests generally consist of lightning impulse and ac voltage tests.

In AC voltage tests, the test voltage values must be calculated carefully and applied according to Figure 20. During the tests, the sub-modules must be short-circuited by closing the S1 bypass switches (Figure 20) to avoid damage to other components of the sub-modules (capacitor, IGBT, IGBT driver, thyristor).

Partial discharge tests mentioned under the section of "AC voltage tests" are very sensitive to application. When performing these tests, it is necessary to turn off all other electrical equipment in the test environment, this is due to avoid effects of other operating systems.

The signal cables used in the test and measurement systems must be shielded and the shields should be grounded at the correct points.

NOMENCLATURES

1. Acronyms

HVDC	High Voltage Direct Current
HVAC	High Voltage Alternative Current
DC	Direct Current
AC	Alternative Current
LCC	Line-Commutated Converter
SCC	Self-Commutated Converter
CSC	Current Source Converter
VSC	Voltage Source Converter
IGBT	Insulated Gate Bipolar Transistors
MMC	Multi Modular Converter
MVU	Multiple Valve Unit
SM	Sub-module
C&P	Control and Protection
FACT	Flexible Alternative Current Transmission
RMS	Root Mean Square
SCR	Short Circuit Ratio
DPS	Dynamic Performance Study

2. Symbols / Parameters

R_f : front resistance

R_t : tail resistance

CL: capacitance of voltage divider

CT: capacitance of transformer

D: diode

R_{ch} : charging resistor

V: generator voltage

L: line inductance

T_1: front time

T_2: time to half value

t_0: time corresponding to virtual zero

t_{30}: time when the impulse first reaches 30% of its peak value

t_{50}: time when the impulse decays to 50% of its peak value

t_{90}: time when the impulse first reaches 90% of its peak value

O_1: virtual zero

U_{tlm}: multiple valve unit lightning impulse test voltage

$LIPL_m$: lightning impulse protective level determined by insulation co-ordination, taking into account the arrester(s) connected between MVU high voltage terminal and earth

k_4: test safety factor, 1.1

k_6: test safety factor, 1.1

k_8: test safety factor, 1.1

k_t: atmospheric correction factor

$U_{tam\text{-}1min}$: multiple valve unit 1 min. AC test voltage

$U_{tam\text{-}30min}$: multiple valve unit 30 min. AC test voltage

U_{mm1}: peak value of maximum voltage between the terminals of the MVU in service, particularly in system fault condition and valve fault operation condition. The over-voltage limiting effect of phase arrester or other over-voltage protection means, if any, shall be taken into account to derive this over-voltage.

U_{mm2}: peak value of the maximum repetitive operating voltage between the terminals of the MVU during steady-state operation, including switching overshoot

$U_{tas\text{-}1min}$: valve support 1 min. AC test voltage

$U_{tas\text{-}30min}$: valve support 30 min. AC test voltage

U_{mS1}: peak value of maximum voltage appearing on the valve support in service, particularly in system fault condition and valve fault operation condition. The over-voltage limiting effect of phase arrester or other over-voltage protection means, if any, shall be taken into account to derive this over-voltage

U_{mS2}: peak value of the maximum repetitive operating voltage across the valve support during steady-state operation, including switching overshoot

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