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HVDC WITH VOLTAGE SOURCE CONVERTERS AND EXTRUDED CABLES FOR UP TO ±300 kV AND 1000 MW

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SUMMARY

VSC HVDC systems have a lot of interesting properties of which the most interesting is the possibility to make connections in or between networks by low weight extruded cables. These connections can be made at a cost that can even be comparable with overhead ac lines. In addition to full power flow control in both directions, the VSC HVDC systems can prevent fault propagation, increase low frequency stability, reduce network losses and increase voltage stability. These attractive features open interesting markets and applications where power shall be transported over long distances at large depths under demanding circumstances and where network stability, safety and reliability are of the highest priority.

Today a maximum power handling of the system of at least 1000 MW at ±300 kV dc is attainable, thanks to synchronized development in four major technical areas: IGBT valves, DC cable system, main circuit of converter station and control system. This paper presents the development in those four areas.

The VSC valves have increased current handling, lower losses, better cooling and more even voltage sharing so they may be built for drastically higher power rating than previously. A new larger presspack IGBT gives higher converter current handling.

The cable system has been expanded in voltage and laying depth. Robust flexible and stiff joints have been developed for the polymeric extruded cables. Testing has proved 300 kVdc capability of the cable system and laying depth larger than 2000 m.

The converter main circuit has been modified for greater simplicity, lower investment cost and lower losses.

The control system has been developed to be more robust and have more control functionalities including black-start control which can provide full support during grid restoration processes.

KEYWORDS

HVDC - VSC - Cable - XLPE - Joint - Submarine - Undergrounding - IGBT - Valve - Control - Converter

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1. Introduction

The electricity networks of today increasingly need control and stability at high levels of loading. Increasing the stability through adding more lines is not always an option due to restrictions in right-of-way or limits to acceptable short circuit current. Here, HVDC transmission solutions using undergrounding through extruded cables systems offer unique advantages. For instance, voltage source converters (VSC) do not add to the short-circuit power while extruded cables systems offer easy installation for both land and submarine applications. Recent developments in four major fields; valves, cable system, system design and HVDC control has opened the possibility to the increase the power rating of VSC based HVDC and greatly expand the area of application.

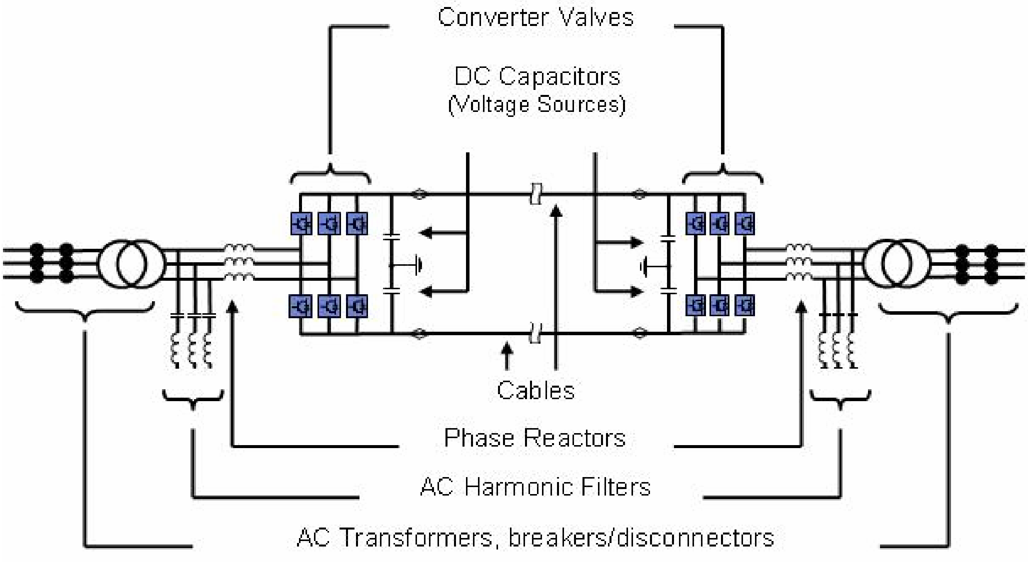

Figure 1: Simplified circuit diagram for 2-level VSC HVDC showing the major components of the system.

2. Valves

Adding more components in series increases DC-voltage handling in a fairly straightforward manner. Current handling may be improved in several ways, whereof the most important are to increase semi-conductor active area in the IGBT-modules, improve cooling and optimize switching.

2.1 Valve Voltage

The largest VSC HVDC converter valves so far delivered were for the Cross Sound Cable project [1] in the North Eastern USA. Those valves are rated ±150 kV dc and handle 330 MW active power at 1050 Arms AC-current. Valves with the same voltage rating are also installed in the Murray Link project. The EstLink project increases the active power to 350 MW, but keeps the dc-voltage at the same level. These projects have prefabricated converter valves mounted in modular metal enclosures.

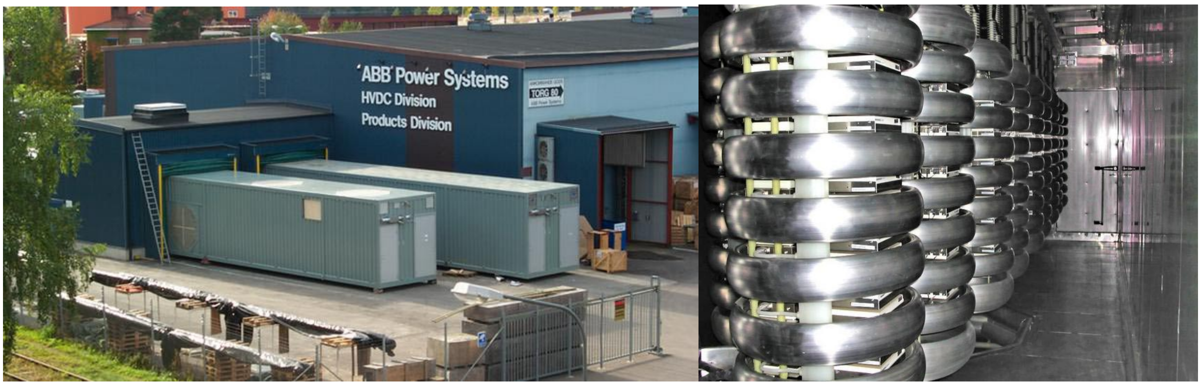

Figure 2. Left: Enclosures for Murraylink converter valves docked to the assembly factory. Right: Inside the enclosure, showing hanging stacks of IGBT's with electric field grading rings. DC voltage is ±150 kV.

Most of the assembly and testing of the valves is performed at the factory in a controlled environment, so the time at site is reduced. The enclosures also separate the valves mechanically and shield the electromagnetic disturbance caused by switching. When increasing the voltage to 300 kV, the enclosure concept will have to be abandoned due to insulation distances.

Increasing the valve switching voltage leads to higher influence of stray capacitances. The effect of this, combined with the commutation inductance in the valve, has to be accounted for in the design. The challenge of increasing the DC voltage to ±300kV is to achieve sufficient voltage sharing between the series-connected IGBT components in both switching and blocking conditions. Intensive tests in laboratory show that desired even voltage sharing among series IGBT components has been realized with advanced valve control.

2.2 Valve current

Lowest valve cost per MW is achieved at maximum AC-current. The main limiting factors are maximum semiconductor temperature and switching capability of the IGBT module. The temperature of the IGBT is governed by the losses generated and the thermal resistance of the cooling arrangement.

Losses come from two main contributors: conduction and switching. Conduction losses may be reduced by using larger semiconductor area. Switching losses depend on the switching time and the voltage and current at the switching instant. The switching frequency then determines the average switching losses. Fast switching and a low switching frequency reduce the power dissipation. However, the switching frequency affects controllability of the converter so there is a trade-off between them. High switching speed, i.e. fast transition between conducting and blocking state, is realized through specially adapted gate driving.

The EstLink project, to be commissioned by the end of 2006, has driven the AC-current requirement from 1050 A to 1130 A at rectifier. This increase of current handling on the same IGBT has been reached by improving the heat sink and by optimizing the switching pattern.

For higher current ratings, there is a need to increase the semiconductor area. Such bigger components have been developed [2]. Using extensive test results from single-pulse tests, frequency tests, power cycling tests, simulations and measurements it is predicted that up to 1740 A converter AC current may be reached.

3. Cable system

The installed amount of polymeric insulated HVDC cable has become impressive. Circa 1200 km cable has been installed since the start at Gotland, Sweden in 1999. [3] The number of in-service years multiplied with the length of cable gives 4200 km x years at the end of 2005.

The first three installations were land cables, but the latest installed cables, the Cross Sound Cable project and the Troll A project [4], are submarine. In the year 2006 another submarine cable project will be realized, the EstLink project.

3.1 Joints

Terminations, stiff prefabricated joints as shown in *Figure 3* for land installation and submarine repair as well as flexible joints were used in these projects.

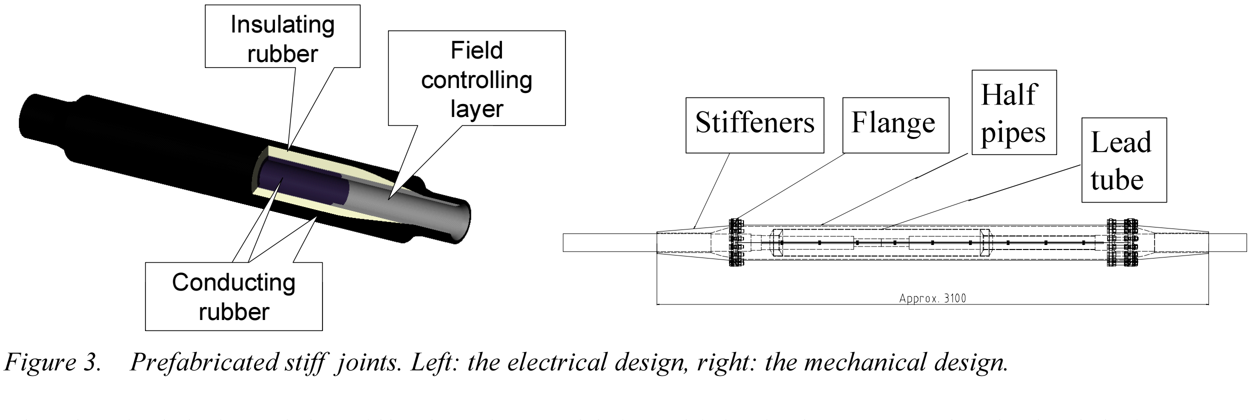

Figure 3. Prefabricated stiff joints. Left: the electrical design, right: the mechanical design.

The electrical design of the stiff submarine prefabricated joint is the same as for the land design, but the mechanical design demands a combination of mechanical strength and water tightness in a more harsh environment. The water tightness was achieved by swaging down a lead sheath over the joint after which it is soldered against the lead sheath of the cable. To maintain and ensure the continuity of the PE-sheath, a heat shrinkable tube was employed over the lead tube. The mechanical protection consists of a galvanized steel pipe and stiffeners giving the joint good crush resistance against a rocky seabed.

The mechanical, thermal and electrical properties of the flexible joint have to match the cable. The conductor joint is therefore TIG-welded. The insulation system is restored by lapping and successively vulcanizing semi-conductive and insulating tapes around the cable. Then the lead-sheath, PE sheath and armoring are restored.

3.2 Increasing the laying depths

The laying depths of the above mentioned projects are moderate; 50 m for Cross Sound Cable and 340 m for Troll A. It is of interest how deep cables can be laid using conventional design technique.

The maximum laying depth of a cable is dictated by its design and by the test force during a mechanical tensile bending test. The test force is calculated using CIGRÉ "Recommendations for mechanical tests on sub-marine cables" published in Electra No.171, April 1997. The test force depends on the cable weight, the allowable bottom tension, and the dynamic tension. The dynamic tension depends on the mass of the cable and the vertical movement and the circular frequency of the laying sheave. One could say that the dynamic tension is defined by the weather and wave conditions.

After test the cable sample undergoes a visual inspection. The test shall not give "permanent deformation of the conductor or armoring" according to the above named recommendation. This is an important and limiting demand. The conductor and armoring may be deformed in terms of local length increase and local diameter decrease. This happens typically at the weakest point of the sample, often the joint. This deformation depends on design parameters as for example maximum allowable tension in conductor and armoring.

As no exact definition is given in Electra's recommendation concerning "permanent deformation" the allowable conductor tension and armor tension are more or less free to choose. Manufacturers tend to stay on the safe side and choose values between 70 and 100 N/mm^2 for jointed copper conductors.

When one allows larger tension, greater laying depths can be reached. To get a rough feeling, some depths are calculated for two different cables and two different wave conditions (See *Table I*).

Table I. Laying depths for different wave heights b_h, movement periods t and cable designs. The tension in the armoring never exceeded 170 N/mm^2.

Cable type	Conductor tension [N/mm^2]	Max. laying depth [m] Wave conditions 1 b_h = 3 meter t = 6 seconds	Max. laying depth [m] Wave conditions 2 b_h = 5 meter t = 12 seconds
Single core, 300 mm^2 copper, 8 mm insulation, 4 mm double steel wire armoring	Very conservative < 70	1050	1150
	Conservative < 100	1500	1650
Single core, 1300 mm^2 copper, 12 mm insulation, 5 mm double steel wire armoring	Very conservative < 70	950	1050
	Conservative < 100	1350	1500

It is concluded that depths up to ca. 1500 meters can be reached with today's conservative technique. Still larger depths can be reached with a more progressive interpretation of Electra No. 171, i.e., to allow a permanent, but small and local deformation of the conductor joint. To prove this, a 300 mm^2 Cu, 8 mm insulation, double steel armored cable including a submarine flexible joint was subjected to a tensile bending test according to Electra No.171. A force of 380 kN was used, resulting in a measured conductor tension of 130 N/mm^2. The test corresponded to a laying depth of more than 2000 meters. An electrical type test according to IEC60840 based on an AC voltage U_0 = 52 kV was performed after the tensile bending test.

- PD test at 39 kV, Tan δ test at 26 kV
- 20 days of heat cycling at 52 kV (4 hours heating, 8 hours cooling, maximum conductor temperature >95°C)
- Hot impulse test at 250 kV (10 positive and 10 negative impulses)
- Power frequency voltage test at 65 kV followed by a PD test at increased voltage (65 kV)

The test was performed with shorter temperature cycle duration to include more cycles within 20 days. However, it was ensured that steady state temperatures for conductor and sheath were reached in each cycle. The objects passed all the tests without any problem. A local permanent maximal decrease in diameter of less than 3% was measured after the test. Demonstrably this had no effect on the functionality of the cable and joint.

3.3 Increasing the voltage

Extruded HVDC cable systems are commercially available up to 150 kV DC. The next step is to develop and commercialize these cable systems at 300 kV DC using the knowledge and design base of the 80 and 150 kV levels. A prototype polymeric 300 kV cable was produced and tested together with prototype accessories. The test program was set up according to CIGRÉ publication "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV". The test steps are listed here below.

- 12 cycles at a negative DC voltage of 1.85 x 300 = -555 kV. Every cycle consisted of 8 hours heating followed by 16 hours of natural cooling.
- 12 cycles at a positive DC voltage of 1.85 x 300 = +555 kV.
- 3 long cycles at a positive DC voltage of 1.85 x 300 = +555 kV. Every cycle consisted of 24 hours heating followed by 24 hours of natural cooling.
- 10 switching surges with U_{p2s} = +630 kV and 10 switching surges with U_{p2o} = -350 kV superimposed on a DC voltage of U_0 = +300 kV DC.
- 10 switching surges with U_{p2s} = -630 kV and 10 switching surges with U_{p2o} = +350 kV superimposed on a DC voltage of U_0 = -300 kV DC.
- After the superimposed switching surge withstand test, the test object was subjected to a negative DC voltage of -555 kV DC during 2 hours.

The test objects passed the tests without any problems. After this type test extra 8/16 cycles were performed at voltages increasing 50 kV per cycle starting at -600 kV. At a negative DC voltage of -740 kV the voltage was not increased anymore, but kept at that level. In total five consecutive 8/16 cycles were performed at this level. After the test was stopped. No breakdown occurred.

4. System design

When designing a VSC HVDC system, a large range of parameters has to be included in the optimization. Two of the main components are investment cost and electrical losses.

Converters are usually more cost-efficient in the high current end of the spectrum, in terms of money per MW. Losses in the converter are basically scalable with power rating. DC cable systems are generally more cost efficient in the high voltage end of the spectrum and the losses are a function of conductor area and current, independent of voltage, in contrast to AC-cables.

Any actual project will in the end have to be justified in economical terms after an evaluation of the total cost of installation, operation and losses compared to system benefits and payback. One important and challenging task for the grid owner will be to put a value on the increased functionality and stability of the grid that comes from introducing VSC HVDC.

4.1 System development

The main purpose of the HVDC system development is to realize a robust and simple construction, while keeping the total operation losses low. The development process involved comprehensive evaluation of station topology, switching frequency of IGBT's, and pulse pattern applied.

The first VSC HVDC system built mainly for demonstration purposes, connecting Hellsjön to Grängesberg in Sweden [5], was inaugurated in May 1997. HVDC VSC and STATCOM's with IGBT's as switching elements [6] have been in commercial operation since 1999. Since then, different topologies and system designs suited for different applications have been studied [7], manufactured and delivered [8]. In the optimization process, the considered key factors were production cost, reliability, losses, delivery time and controllability. Production cost, reliability and delivery time are closely related to the circuit complexity.

Table II. Overview of selected VSC projects showing some examples of the trade-off between the key development factors for VSC HVDC. Estlink is the latest and represents the state of the art of VSC HVDC.

Installation	*In service year*	*Converter Topology*	*Switching pattern*	*Switching frequency [Hz]*	*Controllability*	*Circuit complexity*	*Losses*
Gotland HVDC Light® Tjaereborg Directlink	1999 2000 2000	2-level	Sinus PWM	1950	Excellent	Low Low Low	High
Hagfors SVC Light (and all subsequent installations)	1999	3-level NPC, ungrounded	SFOPWM	1260 - 1650	Excellent	Medium	Medium
Cross Sound Cable Murraylink	2002	3-level all IGBT, grounded	3PWM Sinus PWM	1260 1350	Excellent	Medium Medium	Low
Estlink	2006	2-level	Optimum PWM	1150	Very Good	Low	Low

The range of possible applications for VSC HVDC has expanded due to the increase of voltage and power rating. The ±300 kV dc enables very large transmission distances. The realistically reachable power rating of 1000 MW makes VSC an alternative for large scale transmission in a way that was almost unthinkable ten years ago.

Table III. Expanded matrix with present attainable ratings [Dec 2005] of the converters and cable system. Maximum ratings under typical conditions. Distances are for 4% cable losses.

DC Voltage \ AC Current	580 A_{rms}	1140 A_{rms}	1740 A_{rms}
±80 kV	95 MW / 75 km	185 MW / 150 km	285 MW / 230 km
±150 kV	175 MW / 140 km	350 MW / 280 km	525 MW / 420 km
±300 kV	350 MW / 280 km	700 MW / 560 km	1050 MW / 840 km

5. Control system and VSC application benefits

During the last ten years, a lot of effort has been put into development and refinement of the control system. The main focus has been robustness, high reliability and maximum availability. The control system is designed to ensure desired performance for a range of normal operation conditions and to ensure proper behavior under different AC disturbances. With the voltage source converter there is no commutation failure problem when an AC fault occurs. However, effective suppressing of transient over-voltage and over-current is a challenge to the control design.

It has been widely recognized that VSC based HVDC has many advantages over the classic HVDC [9,10]. AC faults, or other disturbances on one AC network do not propagate to the other if two terminals of HVDC are connected to two different AC networks. The transmission line can keep transferring the active power during one-phase faults and distant three-phase faults if transient overvoltage and overcurrent is avoided by effective control action. This makes the VSC HVDC superior to AC transmission and classic HVDC in transmitting windpower, and feeding power to sensitive loads.

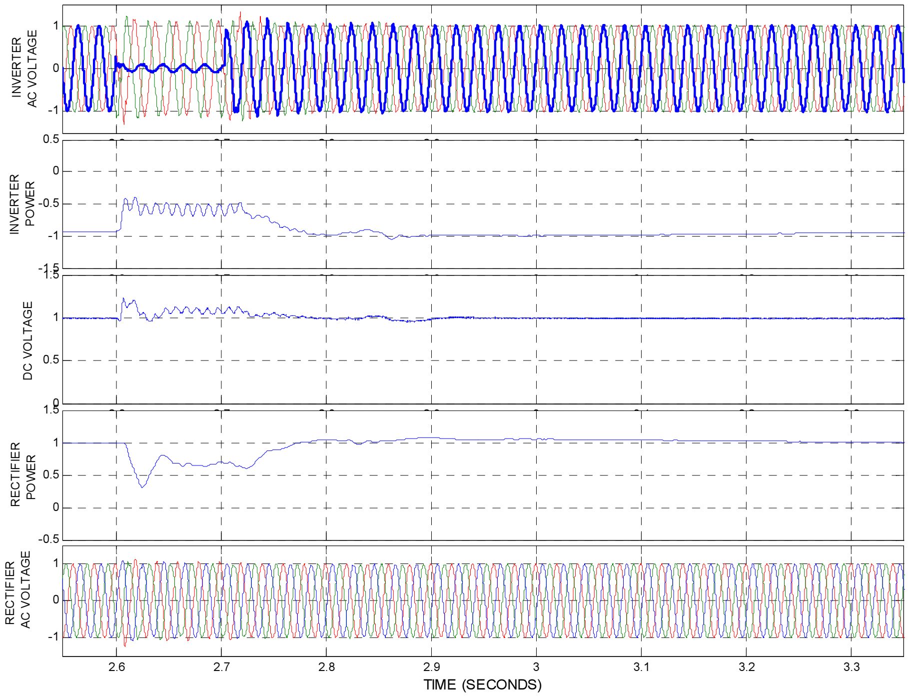

Figure 4 Control performance of a VSC HVDC under a severe one-phase fault on the inverter side. About 70% of pre-fault power is transmitted during the fault, and full power transfer is recovered quickly after the fault is cleared. During the single-phase fault the power on the inverter side is oscillating with 100 Hz. Thanks to an efficient unbalance control, the DC side voltage oscillates at 100 Hz with only a small amplitude and the AC voltage on the rectifier side is scarcely affected by the disturbance. From the top: (All in p.u.) Inverter AC voltage, Inverter power, DC voltage, Rectifier power and Rectifier AC voltage

Another attribute that may be interesting to network planners is that the VSC HVDC can enhance the strength of the AC network via fast dynamic AC voltage control, without increasing the short-circuit current for the existing AC network [11]. This is achieved by flexible AC current control. During a large size AC fault, the AC current from the converter is limited to zero by suitable control action. This attribute will save the cost for renewing AC breakers that would be needed when introducing new AC lines.

The development of a black start function makes it possible for the VSC HVDC to act as a virtual generator for one of the networks in case there is a complete loss of generation. In this case, grid restoration may start from the VSC, or use the VSC as a balancing device when adding more and more generators during the re-activation of the network.

It should also be noted that the ability to control active and reactive power at both AC terminals makes the VSC HVDC a very powerful tool for power flow control. As a result, it is possible to achieve optimization of load flow in the connected AC network in addition to keeping the voltage stable [12].

5.1 Control system testing

All normal operations of the HVDC link and a large number of serious fault cases that are not normally possible to test in the plant, are carried out during the Factory System Test (FST) of the control system. An analog simulator is used to represent relevant parts of the AC and DC systems. Newly developed control and protection philosophies are implemented with software and hardware identical to the delivered system. Results obtained from simulations done in electromagnetic transient programs are verified towards results from the FST. An example is shown in *Figure 5*.

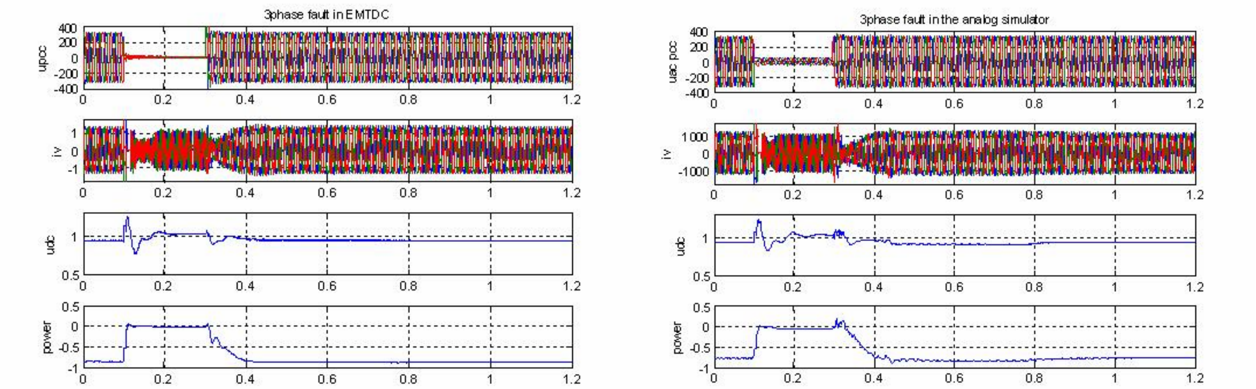

Figure 5. Example comparison between digital simulation of response to 3-phase fault (left) and the real response of the delivery control system connected to an analog simulator (right). Traces from top: AC voltage in faulted network (kV), converter AC current (A), DC voltage (p.u.) and transmitted power (p.u.).

6. Conclusions

The development work for VSC HVDC systems has been discussed. The progress in four key technical aspects of VSC HVDC system indicates that the attainable power rating is increased to 1000 MW. As a result, the range of possible applications for VSC HVDC can be expanded to large scale transmission. The availability of ±300 kV DC makes it possible to transmit large amounts of power long distance. Under restrictions in right-of-way, the VSC HVDC system provides a solution for adding new transmission lines of distance longer than 100 km. Compared to AC, VSC HVDC has additional advantages such as full power flow control in both directions, voltage stabilization via continuous reactive power control and minimized disturbances by preventing fault propagation.

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