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Protection of VSC Controlled HVDCPlus System using PWM Technique

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Abstract - *Rapid development in the field of power electronic devices with turn off capability like Insulated Gate Bipolar Transistors (IGBT) and Gate Turn-Off Thyristors (GTO), makes the Voltage Sourced Converters (VSC) getting more and more attractive for High Voltage Direct Current Transmission (HVDC). This new innovative technology provides substantial technical and economical advantages for different applications compared to conventional HVDC transmission systems based on thyristor technology. This paper focuses on VSC application for HVDC systems of high power ratings (up to 200 MW) which are currently in discussion for several projects. After a brief description of the main circuit components an overview on basic design aspects of VSC based HVDC systems is given along with Fault analysis.*

Key Words: **HVDC, VSC, Harmonic Performance, Insulation Coordination, Transient Stress.**

1. INTRODUCTION

In this paper, we use HVDCplus as a terminology for a HVDC transmission system which is based on VSC technology. The extension 'plus' stands for power link Universal systems and represents economical solutions to the most challenging requirements on power transmission and distribution. Some important highlights are:

- Feeding AC systems with low short circuit power or even passive networks with no local power generation.
- STATCOM functionality, i.e. continuously adjustable reactive power support to the AC system to control AC bus voltage and improve system stability. Active and reactive power exchange can be controlled independently from each other within the total power rating of a station

These features make HVDCPlus an interesting alternative to conventional thyristor based HVDC systems. A conventional HVDC can only operate in AC systems with appropriate short circuit power. Under weak system conditions, rotating synchronous phase shifters, that are expensive both in investment and maintenance, have been used to achieve reliable operation. A HVDCplus converter is equipped with semiconductor devices such as IGBTs that can be turned on and off in a controlled manner. Therefore, the converter is able to function in a system where there is no local generation and can control the ac system voltage and frequency.

Thyristor converters as used in conventional HVDC systems always require reactive power. The reactive power demand varies according to the active power transfer. Additional power components such as switched capacitor banks or Static VAR Compensators (SVC) have been used to supply the reactive power demand of the converter station. In an HVDCplus system, each station can control active and reactive power flow independently from each other within the total MVA power ratings. Thus, the scheme not only can transmit active power from one AC network to another but it also offers the possibility of controlling the AC bus voltage and improving the AC system stability. HVDCplus is seen today a sophisticated alternative to conventional HVDC systems in the fields of

- Interconnecting weak or isolated AC systems
- Interconnecting AC systems in the lower and middle power range.
- Connecting remote isolated loads like off-shore Oil- and Gas-platforms
- Connecting Wind parks (on-shore or off-shore)
- Multi Terminal HVDC systems.

2. HVDCPLUS TRANSMISSION SYSTEMS

HVDCPlus systems are available today for power ratings up to 200 MW for one 12pulse bipolar unit. This power transfer is achieved with DC voltages up to ±150 kV and DC currents up to more than 700 A. Fig. 1 shows the main circuit diagram of a HVDCplus transmission scheme as an example. The transmission system consists of two stations, Station A and Station B, connected by a DC cable or an overhead line. The major power components are

- High voltage DC circuit
- Voltage Sourced Converters (VSC)
- Transformers

The system shown in Fig. 1 is of bipolar type. One station comprises two equally designed VSCs, each providing a DC voltage V_{dc}. The central point of the DC circuit is grounded in one of the stations via grounding impedance and a parallel connected ZnO arrester. The central point of the other station is grounded only by an arrester to prevent current flowing through the ground path.

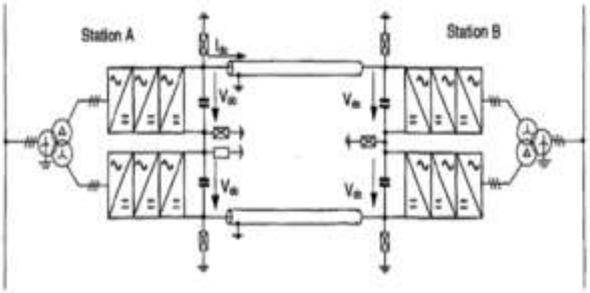


Fig.1: Main circuit diagram of a bipolar HVDCPlus transmission system

Similar to a conventional HVDC HVDCplus scheme can also be built as a mono polar system or as a Back to Back station. The major power components are described in more detail in the following chapters.

2.1. High Voltage DC Circuit

The DC circuit is formed by the storage capacitors and the DC cable or overhead line respectively. A storage capacitor provides the corresponding VSC with a smooth DC voltage of a fixed polarity. To achieve maximum use of the power semiconductors of the VSC, the capacitor needs to be connected to the converter by a low inductive path. The size of the capacity is chosen according to the maximum DC voltage ripple tolerated.

The DC cable can take significant advantage of the fixed polarity of the DC voltage. In conventional thyristor based transmission systems, power reversal is always associated with changing the polarity of the DC voltage. Transient phenomena in the cable required special design measures and higher insulation capability. A HVDCplus system instead cannot change voltage polarity. Power reversal is achieved by changing the direction of DC current instead. This allows to use new extruded DC cables, which are an attractive alternative to self contained oil filled or mass impregnated paper insulated cables as used for conventional thyristor based HVDC systems

2.2. Voltage Sourced Converters for HVDCplus

The world of converters might be divided into two groups that are to be distinguished by their operation principle. One group needs an AC system to operate. The AC system voltage forces the current to commutate from one phase to another. Using controlled semiconductors like thyristors, the point-on-wave for commutation can be chosen and thus, the power exchanged between AC and DC system via the converter can be controlled. Converters that rely on an AC system to operate are called Line Commutated Converters. Conventional HVDC systems employ Line Commutated Converters.

The second group of converters does not need an AC system to operate and is therefore called Self Commutated Converters. Depending on the design of the DC circuit this group can further on be divided into Current Source Converters and Voltage Sourced Converters (VSC). A Current Source Converter operates with a smooth DC current provided by a reactor, while a VSC operates with a smooth DC voltage provided by the storage capacitor

Among the Self Commutated Converters it is especially the VSC that has a long history in the lower power range for industrial drive applications. Operational experience and a broad market of semiconductors might be two important factors promoting VSC to be used in high voltage applications. Static Compensators (STATCOM) like the ±l00 MVAR TVA Statcom [l] or the 320 MVA Unified Power Flow Controller (UPFC) [2] are examples for a new group of so-called Flexible AC Transmission Systems (FACTS) devices that have been successfully operating in high voltage power systems for years.

Introducing VSC technology into HVDC transmission has led to the innovative HVDCPlus transmission system.

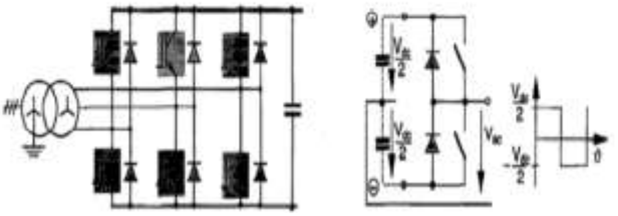


Fig.2: Equivalent circuit of 6 pulse IGBT based 2 level VSC & Basic principle of a 2 level VSC

Fig. 2 shows an equivalent diagram of a VSC as to be used for HVDCPlus transmission systems. It consists of a 6pulse bridge equipped with IGBTs and a anti-parallel connected 6 pulse bridge equipped with free wheeling diodes. Basically, either GTOs or IGBTs can be used as semiconductor switches. To achieve the required power rating, a number of devices is connected in series. GTO valves allow higher currents but less DC voltage than IGBT valves. For HVDCPlus long distance transmission systems high transmission voltages are advantageous to keep transmission losses low. This favors the use of IGBT valves. With the present design and technology, IGBT valves can block up to 150 kV. A VSC equipped with these valves can carry up to 800 A (RMS) AC line current. This results in a power rating of approximately 140 MVA of one VSC.

The basic function of a VSC is to convert the DC voltage of the storage capacitor into AC voltages. Fig. 2 illustrates the basic operating principle. The polarity of the DC voltage of the converter is defined by the polarity of the diode rectifier. The IGBTs can be switched on at any time by appropriate gate voltages. However, if one IGBT of a branch is switched on, the other IGBT must have been switched off before to prevent a short circuit of the storage capacitor. Reliable converter interlock functions will preclude unwanted switching of IGBTs. Alternating switching the IGBTs of one phase module as shown in Fig. 3 successively connects the AC Terminal of the VSC to the plus tapping and the minus tapping of the DC capacitor. This results in a stair stepped AC voltage comprising two voltage levels: +Vdc/2 and - Vdc/2. A VSC as shown in Fig. 2 is therefore called a 2 level converter

Due to a switching frequency, that is considerably higher than the AC system power frequency, the wave shape of the converter AC current will be controlled to be very sinusoidal. This is achieved by special “Pulse Width Modulation”(PWM) methods. The three level converter comprises 4 valves in one phase leg as shown in Fig. 4. The switching rule is that only two valves that are directly connected in series can be switched on at a time, i.e. S1 and S2 or S2 and S3 or S3 and S4. Switching on S1 and S2 connects to the plus tapping, S2 and S3 connects via the clamping diodes to the mid-point tapping (MP), S3 and S4 connects to the minus tapping of the DC circuit to the AC terminal of the phase leg. Thus, the resulting voltage on the AC terminal comprises three levels instead of two in case of a 2level converter.

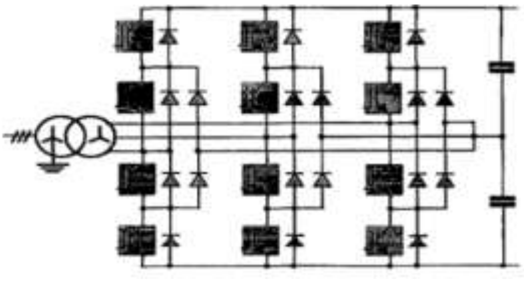


Fig.3: Equivalent circuit of 6 pulse IGBT based 3 level VSC

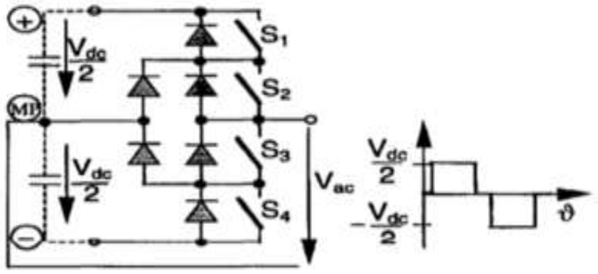


Fig.4: Basic principle of a 3 level VSC

2.3 Pulse width modulation:

Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a modulation technique used control of the power supplied to electrical devices. The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast rate. The longer the switch is on compared to the off periods, the higher the total power supplied to the load. The PWM switching frequency has to be much higher than what would affect the load (the device that uses the power), which is to say that the resultant waveform perceived by the load must be as smooth as possible. The rate (or frequency) at which the power supply must switch can vary greatly depending on load and application, for example. Switching has to be done several times a minute in an electric stove; 120 Hz in a lamp dimmer; between a few kilohertz (kHz) and tens of kHz for a motor drive; and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero.

2.4 Transformers

Normally, the converters are connected to the AC system via transformers. The most important functions of the transformers are:

1. To provide a reactance between converter AC terminals and AC system
2. To transform the voltage of the AC system to a value optimized to the converter voltages and currents
3. To connect two single 6pulse converters to form a 12pulse group
4. To connect two single converters with different DC potentials to ground.

However, in some cases functions 2 to 4 might not be an issue for the design concept of a HVDCplus system. If, for example, functions 2, 3 and 4 do not apply, because the present AC system voltage matches the converter voltages and currents, and there is just one converter per station necessary to transmit the required power, then function 1 can be taken by a reactor coil leading to a more simple station design and considerable cost savings.

Transformer or reactor is exposed to the converter AC voltage which has a rectangular wave shape as shown in Fig. 4. A 2 level converter will frequently change the potential between the phases from zero to V_{dc} within a couple of microseconds. Steep voltage steps like these results in high stresses of the insulation materials. A low-pass filter connected to the AC terminals of the converter might be used, to lower dv/dt values.

2.5 Basic building blocks of HVDC Plus system.

AC System:-

An analog signal is a signal that can be continuously, or infinitely, varied to represent any small amount of change. Pneumatic, or air pressure, signals used to be used predominately in industrial instrumentation signal systems. This has been largely superseded by analog electrical signals such as voltage and current. To understand the ways in which an analog signal is transmitted over a circuit, it is first important to understand the relationships that make analog signal transmission possible. It is the fundamental relationship between voltage, current, and electrical resistance that allow either a continuously varying current or voltage to represent a continuous process variable.

Rectifiers:-

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. A rectifier is an electrical device composed of one or more diodes that converts alternating current (AC) to direct current (DC). A diode is like a one-way valve that allows an electrical current to flow in only one direction. This process is called rectification. A rectifier can take the shape of several different physical forms such as solid-state diodes, vacuum tube diodes, mercury arc valves, silicon-controlled rectifiers and various other silicon-based semiconductor switches.

Power Cables:-

A power cable is an electrical cable, an assembly of one or more electrical conductors, usually held together with an overall sheath. The assembly is used for transmission of electrical power. Power cables may be installed as permanent wiring within buildings, buried in the ground, run overhead, or exposed. The electrical wires are normally made of copper. It is very good conductor, has good malleability and ductility.

Inverter:-

A power inverter, or inverter, is an electronic device or circuitry that changes direct current (DC) to alternating current (AC).The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. Inverters can also be used with transformers to change a certain DC input voltage into a completely different AC output voltage (either higher or lower) but the output power must always be less than the input power: it follows from the conservation of energy that an inverter and transformer can't give out more power Inverter Function and Benefits. Batteries produce power in direct current (DC) form, which can run at very low voltages but cannot be used to run most modern household appliances. Utility companies and generators produce sine wave alternating current (AC) power.

Data acquisition:-

Data acquisition is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer. A DAQ system consists of sensors, DAQ measurement hardware, and a computer with programmable software. Compared to traditional measurement systems, PC-based DAQ systems exploit the processing power, productivity, display, and connectivity capabilities of industry-standard computers providing a more powerful, flexible, and cost-effective measurement solution.

- Sensors, to convert physical parameters to electrical signals.
- Signal conditioning circuitry, to convert sensor signals into a form that can be converted to digital values.
- Analog-to-digital converters, to convert conditioned sensor signals to digital values.

2.6 Harmonics

Like all power electronic converters, VSCs generate harmonic voltages and currents in the ac and dc systems connected. In a simplified manner, a VSC can be considered a harmonic voltage source behind the impedance of the converter transformer. In the same way, a VSC can be considered a harmonic current source connected in parallel to the storage capacitor.

Harmonics generated depend on:

- the station topology(e.g. 6 pulse or 12 pulse)
- the switching frequency of IGBT's
- the pulse pattern applied.

Using 12 pulse configuration instead of 6 pulse will improve harmonic conditions both on AC and DC side. Characteristic AC side harmonics will have the ordinal numbers $V_{AC}=12_n+1$; n=1,2, ..., characteristic DC harmonics will have the ordinal numbers $V_{DC=}12n$; n=1,2, ...All other harmonics will be cancelled out under ideal conditions.

Sophisticated PWM methods allow to eliminate critical harmonics employing special optimized pulse patterns. In most cases, such special designed pulse patterns allow the converters to be operated at lower switching frequencies than would be necessary in case of delta-sinus modulation to meet harmonic performance requirements. Switching frequency, pulse patterns and operation losses are therefore seen as key issues of the design optimization process of a HVDCPlus transmission scheme.

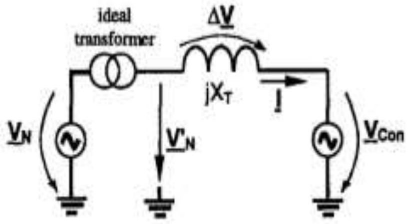


Fig.5: Equivalent circuit to calculate fundamental load flow between VSC and AC system

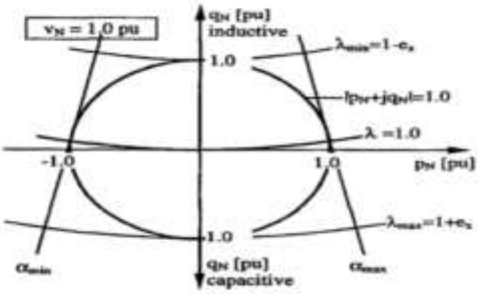


Fig.6: PQ diagram of HVDCPlus station

Due to its inherent harmonic elimination capability the harmonic interference of VSC converter is rather small in comparison to the conventional line commutated converters. However, harmonic filters might be necessary on the ac and dc sides depending on the harmonic performance requirements both for ac and dc side, ac system harmonic impedance, dc line /cable impedance and loss evaluation.

2.7 Insulation Coordination

Surge arresters are used to protect the HVDCplus power components against transient over-voltages such as lightning and switching surges. The following arresters shall be normally installed on AC- and DC-side respectively:
a) AC-side arresters: - AC bus arrester
- AC filter arrester if applicable
b) DC-side arresters: - DC line arrester
- Neutral bus arrester
- DC filter arrester if applicable.

Calculation and selection of the Maximum Continuous Operating Voltage (MCOV) of the arresters is based on the maximum voltage which can appear during continuous operation. Some extra margin is added to cover temporary operating conditions, measuring tolerances etc.

The arrester ratings are derived as maximum values from several fault cases. The insulation strength of equipment for lightning and switching stresses are chosen on basis of calculated over-voltages. The minimum margins used for determination of withstand levels for each equipment are chosen in accordance to practice on conventional HVDC and to IEC 6007 1-5.

3. DESIGN CONSIDERATIONS

Steady State Characteristics

Fig. 6 shows a simplified single line diagram to calculate the fundamental load flow between AC system and one of the HVDC Plus VSCs. The AC system as well as the converters are considered voltage sources. These voltage sources are connected via the transformer, represented as an ideal transformer and a leakage impedance. While magnitude and phase angle of the AC system voltage V_N or $V|_N$ & respectively is determined by the load flow of the AC system, magnitude and phase angle of the converter voltage V_{Con} can be adopted by the converter control. According to Kirchhoff's law, controlling V_{Con} relatively to V_N results in a corresponding voltage drop ΔV across the transformer leakage impedance X_T. Neglecting losses, the current I through X_T, lags by 90^0electrical. As a consequence, controlling V_{Con} determines the current I.

Fig. 7 shows the relations between voltages and currents for an operating point as an example. The current I can be split up regarding $V|_N$ & into one component that is in parallel and into another component that is in quadrature.

The active and reactive power exchange as seen from the AC system terminals of the transformer can be calculated according to the following formulas

$$P_N = \frac{v_N^2}{e_x}\lambda\sin(\alpha);$$
$$q_N = \frac{v_N^2}{e_x}(1-\lambda\cos(\alpha)) \qquad (1)$$

with

$V_{N=}\frac{V_N}{V_{Nn}}$; $P_{N=}\frac{P_N}{S_{bT}}$; $q_{N=}\frac{Q_N}{S_{bT}}$; $e_{x=}X_T\frac{S_{bT}}{V_n^2}$; $\lambda=\frac{V_{con}}{V_N}$

V_N: present magnitude of the AC system voltage.
V_{Nn}: magnitude of the AC system nominal voltage.
V_{con}: present magnitude of the converter AC voltage.
P_N: present active power exchang from the AC system.
Q_N: present reactive power exchange as seen from the AC system.
S_{bT}: rated apparent power of the transformer.

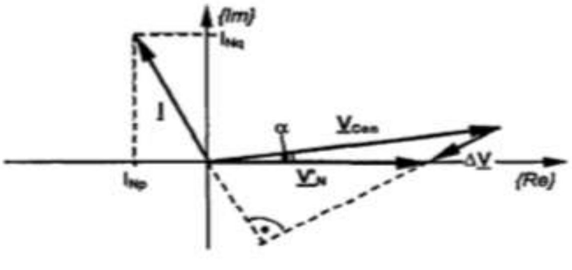


Fig.7: Vector diagram

Considering a certain AC system voltage V_N, the operating range of a HVDC plus station regarding active and reactive power can be visualized using a PQ-diagram as shown in Fig. 8. Keeping the angle α constant while varying λ results in straight lines as shown for α_{max} and α_{min}. Keeping λ constant while varying α results in concentric circles as shown for λ_{max}, λ=1.0 and λ_{min}. The power rating of the station is marked by the circle $|p_N+jq_N|=1.0$ pu. Adjusting the parameters λ and α accordingly, the VSC can operate at any operating point on the circle area continuously. It can therefore control active and reactive power exchange independently from each other. If there is no active power transfer required, a station still can serve as a STATCOM providing capacitive or inductive reactive power support to the AC system it is connected to.

4. TRANSIENT STRESSES

Similar to any other equipment in power systems, components of an HVDCplus system might be exposed to transient voltage and current stresses as a result of several fault scenarios. Fig. 8 shows some characteristic fault cases that are regarded for the design of a HVDCPlus system. Faults are to be distinguished regarding the place they could happen between external faults (faults outside the transmission scheme, within the AC system) and internal faults (faults inside the transmission scheme).

Regarding external faults, the concept is not only to protect the equipment but also to provide best support to the faulty AC system. Depending on the fault clearing strategy, this support might include dynamic voltage control and power oscillation damping after voltage recovery. A HVDCplus station can take advantage of the fast reactive power control capability combined with the possibility to feed or absorb active power

Internal faults will be precluded to the largest extent possible using appropriate design margins for any component and a safe station layout. However, in the event of an internal fault, all components will be protected by fast acting protection systems.

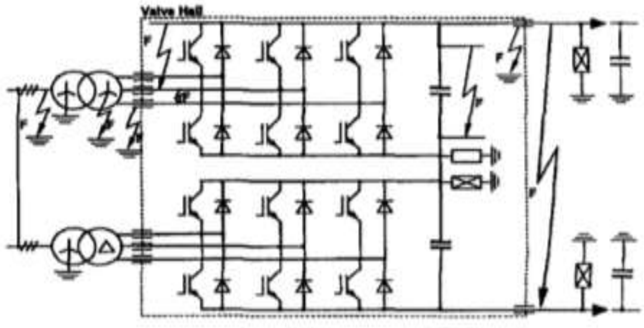
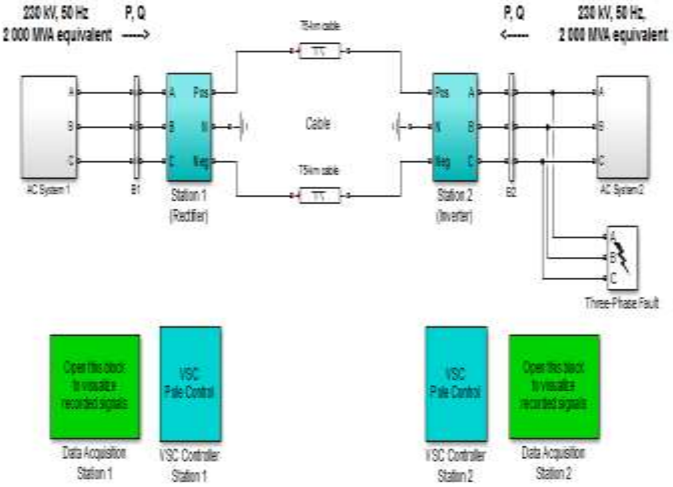


Fig.8: Decisive Fault Scenarios

The fig. 8 shows the fault scenarios. Based upon real time conditions the HVDCplus system can mitigate fault in fraction of time and attain stability immediately.

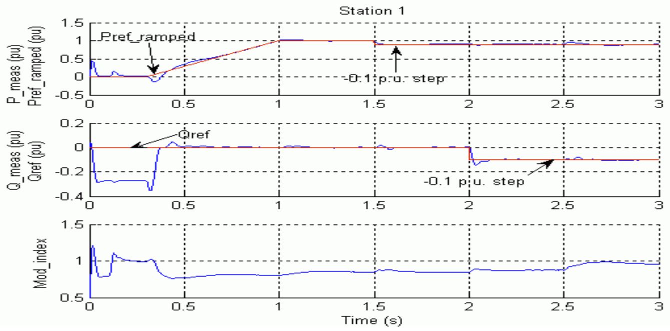
5. FAULT ANALYSIS



A three phase fault at bus 2 leads to transients in system which are cleared in a fraction of time as can be seen from the results displayed below.

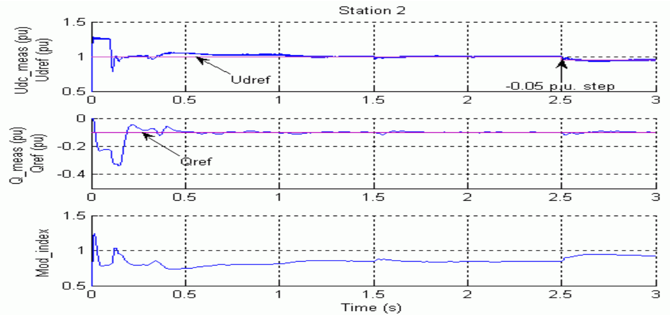
6. RESULT DESCRIPTION

Startup and P & Q Step Responses in Station 1



The main waveforms from the scopes are reproduced below.

Startup and Udc Step Response in Station 2



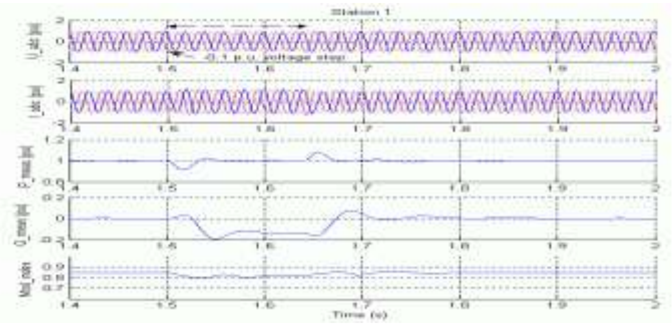
Station 2 converter controlling DC voltage is first de blocked at t=0.1 s. Then, station 1 controlling active power converter is de blocked at t=0.3 s and power is ramped up slowly to 1.0 pu. Steady state is reached at approximately t=1.3 s with DC voltage and power at 1.0 pu (200 kV, 200 MW). Both converters control the reactive power flow to a null value in station 1 and to 20 MVAR (-0.1 pu) into station 2 system.

After steady state has been reached, a -0.1 pu step is applied to the reference active power in converter 1 (t=1.5 s) and later a -0.1 pu step is applied to the reference reactive power (t=2.0 s). In station 2, a -0.05 pu step is applied to the DC voltage reference. The dynamic response of the regulators are observed. Stabilizing time is approximately 0.3 s. The control design attempts to decouple the active and reactive power responses. Note how the regulators are more or less mutually affected.

AC Side Perturbations

From the steady-state condition, a minor and a severe perturbation are executed at station 1 and 2 systems respectively. A three-phase voltage sag is first applied at station 1 bus. Then, following the system recovery, a three-phase to ground fault is applied at station 2 bus. The system recovery from the perturbations should be prompt and stable. The main waveforms from the scopes are reproduced in the two figures below.

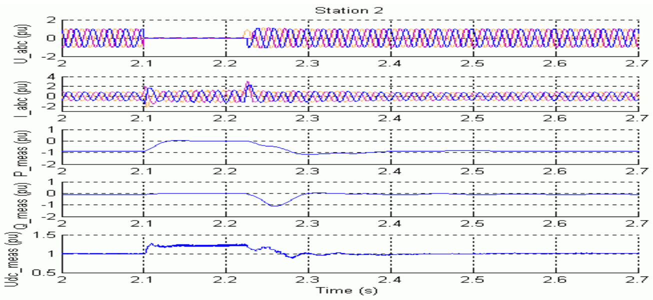
Voltage Step on AC System 1



The AC voltage step (-0.1 pu) is applied at t=1.5 s during 0.14 s (7 cycles) at station 1. The results show that the active and reactive power deviation from the pre-disturbance is less than 0.09 pu and 0.2 pu respectively. The recovery time is less than 0.3 s and the steady state is reached before next perturbation initiation.

The fault is applied at t=2.1 s during 0.12 s (6 cycles) at station 2.

Three-Phase to Ground Fault at Station 2 Bus



Note that during the three-phase fault the transmitted DC power is almost halted and the DC voltage tends to increase (1.2 pu) since the DC side capacitance is being excessively charged. A special function (DC Voltage Control Override) in the Active Power Control (in station 1) attempts to limit the DC voltage within a fixed range. The system recovers well after the fault, within 0.5 s. Note the damped oscillations (around 10 Hz) in the reactive power.

7. CONCLUSION

The terminology HVDCPlus represents the latest technology on high power transmission and distribution applications. Innovative VSC allow high DC voltages of up to 150 kV per VSC and AC currents up to 800A.This results in a very economic design of a +_150 kV bipolar transmission system for power ratings up to 200 MW. A HVDCPLUS system not only transmits active power from one system to the other but also comprises STATCOM functionality. Limited only by the power rating of a station the system can freely control the reactive power exchange with the AC systems. That saves extra investment on capacitor banks or SVC, that would be necessary in case of conventional HVDC systems to compensate the reactive power demand of the thyristor controlled converters. The VSCs are equipped with modem IGBTs. An IGBT combines the advantages of a GTO in terms of high power switching capability with those of a transistor regarding controllability of voltages and currents both in On- and Off- state. This results in a robust converter design and contributes to a high reliability of the overall transmission scheme. The described HVDCPLUS transmission system provides attractive technical advantages for applications like interconnecting (point to point or multi-terminal) very weak ac systems in the lower and middle power range.

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