**6. VOLTAGE SOURCED CONVERTER (VSC) BASED HVDC**

**TRANSMISSION SYSTEM**

With the development of power electronic technology and the relatively high switching frequency of Pulse Width Modulation (PWM), HVDC transmission system based on Voltage Source Converters (VSCs) has taken on some excellent advantages. The new VSC-HVDC system known as “HVDC Light” or “HVDC Plus” [1,2] by leading vendors, has been applied in several special occasions such as the connection of off-shore wind farms or oil drilling platforms into the mainland electrical network and for underground transmission or distribution systems within congested cities. The differences in structure between the two types of converters (Conventional HVDC and VSC-HVDC) contribute to the differences in their performance. Generally, the new transmission technology has the following advantages compared with conventional, thyristor based HVDC:

* Possibility to control the reactive power (consumed or generated by the converter)
* Independently of the active power (to or from the converter).
* No risk of commutation failures in the converter.
* Ability to connect to weak AC networks, or even dead networks.
* Faster response due to increased switching frequency (PWM).
* Minimal environmental impact.

However, VSC transmission does have some disadvantages, which include potentially high power losses and high capital costs when compared with conventional HVDC, but the technology continues to evolve. This presents the elements of VSC-HVDC which uses twelve pulse three level converter topology and its control design. The paper wills first give a brief description about the VSC based HVDC transmission system and its terminal control functions. Following that typical operating contingency scenarios are simulated in order to evaluate transient performance. The simulation results confirm that the control strategy has fast response and strong stability.

* **Fundamentals of VSC transmission**

The fundamentals of VSC transmission operation may be explained by considering each terminal as a voltage source connected to the AC transmission network via a three-phase reactor. The two terminals are interconnected by a DC link, as schematically shown in Fig. 6.1.



**Fig 6.1 Basic VSC transmission**

Fig. 6.2 shows a phasor diagram for the VSC converter connected to an AC network via a transformer inductance. The fundamental voltage on the valve side of the converter transformer, i.e. *UV(1)*, is proportional to the DC voltage as been expressed in Eq(1):

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The quantity *ku* can be controlled by applying additional number of commutation per cycle, i.e. applying pulse width modulation (PWM). Using the definition of the apparent power and neglecting the resistance of the transformer results in the following equations for the active and reactive power:

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The active and reactive power will in the following be defined as positive if the powers flow from the AC network to the converter. The phase displacement angle δ will then be positive if the converter output voltage lags behind the AC voltage in phase.

Equation (2) gives that the active power is proportional to the DC current and the DC voltage. Furthermore it is mainly determined by the phase-displacement angle δ. A positive phase-shift results in that the active power flows from the AC network to the converter. However the reactive power is mainly determined by the difference between the magnitudes of the AC bus voltage and the converter output voltage according to the Eq(3). The reactive power is fed from the voltage with higher magnitude towards the voltage with the lower magnitude.



**Fig 6.2 Phasor diagram of VSC and direction of power flows**

These features permit the independent control of the reactive and active power which is a major advantage for the VSC. P-Q diagram is a circle according to Eq(4) with the centre not located at origin as it does for the line commutated converters as shown in Fig. 3.



**Fig 6.3 P-Q characteristics of a VSC-HVDC system**

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If the output voltage of the converter *UV (1)* is reduced, i.e., by using PWM, supply of

any active and reactive power within the circle is possible.

* **System description**

A 200 MW (± 100 kV) forced-commutated voltage-sourced converter (VSC) interconnection is used to transmit DC power from a 230 kV, 2000 MVA, 50 Hz system to another identical AC system. The AC systems (1 and 2) are modeled by damped L-R equivalents with an angle of 80 degrees at fundamental frequency and at the third harmonic.

The rectifier and the inverter are three-level Neutral Point Clamped (NPC) VSC converters using close IGBT/Diodes. The rectifier and the inverter are interconnected through a 100 km cable (i.e. 2 pi sections) and two 8 mH smoothing reactors. The sinusoidal pulse width modulation (SPWM) switching uses a single-phase triangular carrier wave with a frequency of 27 time’s fundamental frequency (1350 Hz). A converter transformer (Wye grounded /Delta) is used to permit the optimal voltage transformation. The present winding arrangement blocks tripplen harmonics produced by the converter. The 0.15 pu phase reactor with the 0.15 pu transformer leakage reactance permits the VSC output voltage to shift in phase and amplitude with respect to the AC system Point of Common Coupling (PCC) and allows control of converter active and reactive power output. The tap position is rather at a fixed position determined by a multiplication factor applied to the primary nominal voltage of the converter transformers. The multiplication factors are chosen to have a modulation index around 0.85 (transformer ratios of 0.915 on the rectifier side and 1.015 on the inverter side).

To meet AC system harmonic specifications, AC filters form an essential part of the scheme. They can be connected as shunt elements on the AC system side or the converter side of the converter transformer. Since there are only high frequency harmonics, shunt filtering is therefore relatively small compared to the converter rating. The 40 MVAR shunt AC filters are 27th and 54th high-pass tuned around the two dominating harmonics.

* **VSC-HVDC Control strategy**

Fig. 4 shows an overview diagram of the VSC control system and its interface with the main circuit [6]. The converter 1 and converter 2 controller designs are identical. The two controllers are independent with no communication between them. Each converter has two degrees of freedom. In our case, these are used to control:

* *P* and *Q* in station 1 (rectifier)
* *Ud* and *Q* in station 2 (inverter).
* **Phase locked loop**

The phase locked loop (PLL) shown in fig.4 is used to synchronise the converter control with the line voltage and also to compute the transformation angle used in the *d-q* transformation.

The PLL block measures the system frequency and provides the phase synchronous angle *Ө* for the d-q transformations block. In steady state, sin*(Ө)* is in phase with the fundamental (positive sequence) of α component and phase A of the point of common coupling voltage (*Uabc*).



**Fig 6.4 Overview diagram of the VSC control system**

* **Outer active and reactive power and voltage loop**

The active power or the DC voltage is controlled by the control of δ and the reactive power is controlled by the control of the modulation index (*m*). The instantaneous real and imaginary power of the inverter on the valve side can be expressed in terms of the *dq* component of the current and the voltage on the valve side as follows:

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If the reference of the *dq*-frame is selected such that the quadrature component of the voltage is being very small and negligible (*uLq* ≈ 0) then the Eq(5) and Eq(6) indicate that the active and the reactive power are proportional to the *d* and *q* component of the current respectively. Accordingly, it is possible to control the active power (or the DC voltage or the DC current) and the reactive power (or the AC bus voltage) by control of the current components *ivd* and *ivq* respectively. The active and reactive power and voltage loop contains the outer loop regulators that calculate the reference value of the converter current vector (*I\*dq*) which is the input to the inner current loop.

* **Inner Current Loop**

For each of the phases we can write:

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During unbalanced operation [7], the expression for the voltage drop over the reactor ( *R* + *j*ω*L* ) holds for positive as well as for negative-sequence voltages and currents. The voltages drops are described by the differential equation:

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Where *X* =(*p*) for positive sequence and (*n*) for negative sequence. Equation (8) can be transformed to the *α β*-frame. This gives for the voltages and currents:

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Eq(9) can be further transferred into the rotating *dq*-frame:

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The positive and negative sequence voltages of the VSC side are obtained from (10)

and (11):

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The mean voltages over the sample period *k* to *k+1* are derived by integrating (12),

(13), (14) and (15) from *kTs* to *(k+1)Ts* and dividing by *Ts* (where *Ts* is the sampling time).

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and

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By assuming linear current and constant network voltage (the network voltage varies very little during a switching time period) during one sample period *Ts* we obtain from (16) through (19):

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The control is based on (20), (21), (22) and (23), where the voltages and currents at

time (*k+1*) are thus equal to the reference values at time step (*k*).

* **DC Voltage Balance Control**

The difference between the DC side voltages (positive and negative) are controlled to keep the DC side of the three level bridge balanced (i.e., equal pole voltages) in steady-state. Small deviations between the pole voltages may occur at changes of active/reactive converter current or due to nonlinearity on lack of precision in the execution of the pulse width modulated bridge voltage. Furthermore, deviations between the pole voltages may be due to inherent unbalance in the circuit components impedance.