Hybrid Multilevel VSC with AC-Side Cascaded H-Bridge Cells In VSC-HVDC Transmission System

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Abstract-The proposed HVDC system offers the operational flexibility of VSC based systems in terms of active and reactive power control, in addition to improved ac fault ride-through capability and the unique feature of current-limiting capability during dc side faults. Additionally, it offers features such as smaller footprint and a larger active and reactive power capability curve than existing VSC-based HVDC systems, including those using modular multilevel converters. To illustrate the feasibility of the proposed HVDC system, this paper assesses its dynamic performance during steady-state and network alterations, including its response to ac and dc side faults. Long extra high voltage (EHV) AC lines cannot be loaded to their thermal limits in order to keep sufficient margin against transient instability. No alterations of conductors, insulator strings, and towers of the original line are needed.

***Index Terms*—DC fault reverse blocking capability, hybrid multilevel converter with ac side cascaded H-bride cells, modular multilevel converter, voltage-source-converter high-voltage dc (VSC-HVDC)transmission system.**

I. INTRODUCTION

I N the last decade, voltage-source-converter high-voltage dc (VSC-HVDC) transmission systems have evolved from simple two-level converters to neutral-point clamped converters and then to true multilevel converters such as modular converters This evolution aimed to lower semiconductor losses and increase power-handling capability of VSC-HVDC transmission systems to the level comparable to that of conventional HVDC systems based on thyristor current-source converters, improved ac side waveform quality in order to minimize or eliminate ac filters, reduced voltage stresses on converter transformers, and reduced converter overall cost and footprint.

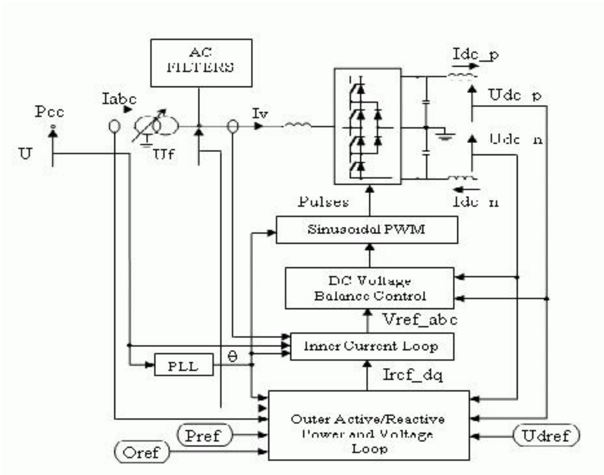
The increasing rating and improved performance of self-commutated semiconductor devices have made possible High Voltage DC (HVDC) transmission based on Voltage-Sourced Converter (VSC). Two technologies offered by the manufacturers are the HVDC Light and the HVDC.The example described in this section illustrates modeling of a forced-commutated Voltage-Sourced Converter high-voltage direct current (VSC-HVDC) transmission link. The objectives of this example are to demonstrate the use of Sim Power Systems™ blocks in the simulation of a HVDC transmission link based on three-level Neutral Point Clamped (NPC) VSC converters with single-phase carrier based Sinusoidal Pulse Width Modulation (SPWM) switching. Perturbations are applied to examine the system dynamic performance. Description of the HVDC Link-The principal characteristic of VSC-HVDC transmission is its ability to independently control the reactive and real power flow at each of the AC systems to which it is connected, at the Point of Common Coupling (PCC). In contrast to line-commutated HVDC transmission, the polarity of the DC link voltage remains the same with the DC current being reversed to change the direction of power flow.

The HVDC link described in this example is available in the power hvdc- vsc model. You can run the command by entering the following in the MATLAB® Command Window: power hvdc vsc. Load this model and save it in your working directory as case5 to allow further modifications to the original system. This model shown on VSC-HVDC Transmission System Model represents a 200 MVA, +/- 100 kV VSC-HVDC transmission link.

II.VSC Control System

Overview of the Control System of a VSC Converter and Interface to the Main Circuit shows an overview diagram of the VSC control system and its interface with the main circuit

Overview of the Control System of a VSC Converter and Interface to the Main Circuit



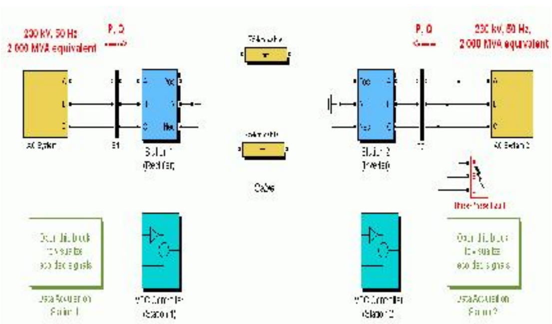
The converter 1 and converter 2 controller designs are identical. The two controllers are independent with no communication between them. Each converter has two degrees of freedom. In our case, these are used to control:

- P and Q in station 1 (rectifier)
- Udc and Q in station 2 (inverter).

The control of the AC voltage would be also possible as an alternative to Q. This requires an extra regulator which is not implemented in our model.

A high level block diagram of the Simulink® discrete VSC controller model is shown in High Level Block Diagram of the Discrete VSC Controller.

VSC-HVDC Transmission System Model



The 230 kV, 2000 MVA AC systems (AC system1 and AC system2 subsystems) are modeled by damped L-R equivalents with an angle of 80 degrees at fundamental frequency (50 Hz) and at the third harmonic. The VSC converters are three-level bridge blocks using close to ideal switching device model of IGBT/diodes. The relative ease with which the IGBT can be controlled and its suitability for high-frequency switching, has made this device the better choice over GTO and thyristors. Open the Station 1 and Station 2 subsystems to see how they are built.

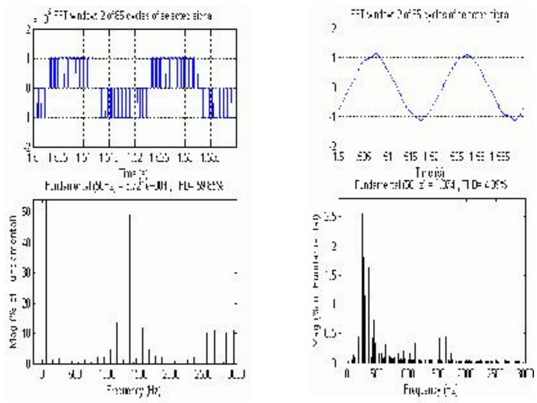
A converter transformer (Wye grounded /Delta) is used to permit the optimal voltage transformation. The present winding arrangement blocks tripplen harmonics produced by the converter. The transformer tap changer or saturation are not simulated. The tap position is rather at a fixed position determined 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). The converter reactor and the transformer leakage reactance permit the VSC output voltage to shift in phase and amplitude with respect to the AC system, and allows control of converter active and reactive power output.

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. It is sufficient with a high pass-filter and no tuned filters are needed. The later arrangement is used in our model and a converter reactor, an air cored device, separates the fundamental frequency (filter bus) from the raw PWM waveform (converter bus). The AC harmonics generation [4] mainly depends on the:

- Type of modulation (e.g. single-phase or three-phase carrier based, space vector, etc.)
- Frequency index p = carrier frequency / modulator frequency (e.g. $p = 1350/50 = 27$)
- Modulation index m = fundamental output voltage of the converter / pole to pole DC voltage

The principal harmonic voltages are generated at and around multiples of p. The shunt AC filters are 27th and 54th high pass totaling 40 Mvar.

Phase A Voltage and FFT Analysis: (a) Converter Bus (b) Filter Bus



(a) (b)

The reservoir DC capacitors are connected to the VSC terminals. They have an influence on the system dynamics and the voltage ripple on the DC side. The size of the capacitor is defined by the time constant τ corresponding to the time it takes to charge the capacitor to the base voltage (100 kV) if it is charged with the base current (1 kA). This yields

$$\tau = C \cdot Z_{base} = 70e\text{-}6 \cdot 100 = 7 \text{ ms}$$

with $Z_{base} = 100\text{kV}/1\text{ kA}$

The DC side filters blocking high-frequency are tuned to the 3rd harmonic, i.e., the main harmonic present in the positive and negative pole voltages. It is shown that a reactive converter current generate a relatively large third harmonic in both the positive and negative pole voltages [3] but not in the total DC voltage. The DC harmonics can also be zero-sequence harmonics (odd multiples of 3) transferred to the DC side (e.g., through the grounded AC filters). A smoothing reactor is connected in series at each pole terminal.

To keep the DC side balanced, the level of the difference between the pole voltages has to be controlled and kept to zero (see the DC Voltage Balance Control block in the VSC Controller block).

The rectifier and the inverter are interconnected through a 75 km cable (2 pi sections). The use of underground cable is typical for VSC-HVDC links. A circuit breaker is used to apply a three-phase to ground fault on the inverter AC side. A Three-Phase Programmable Voltage Source block is used in station 1 system to apply voltage sags.

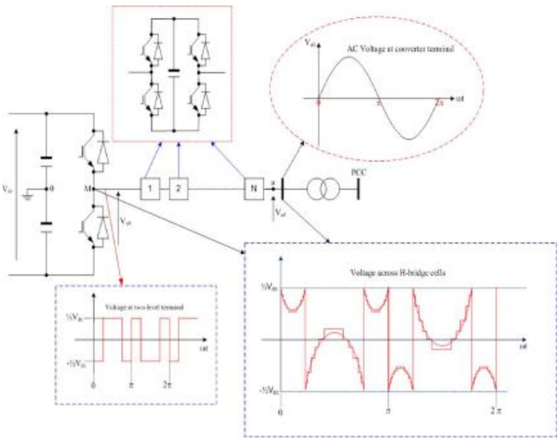


Fig. 2. Hybrid voltage multilevel converter with ac side cascaded H-bridge cells.

HYBRID MULTILEVEL VSC WITH AC-SIDE CASCADED H-BRIDGE CELLS

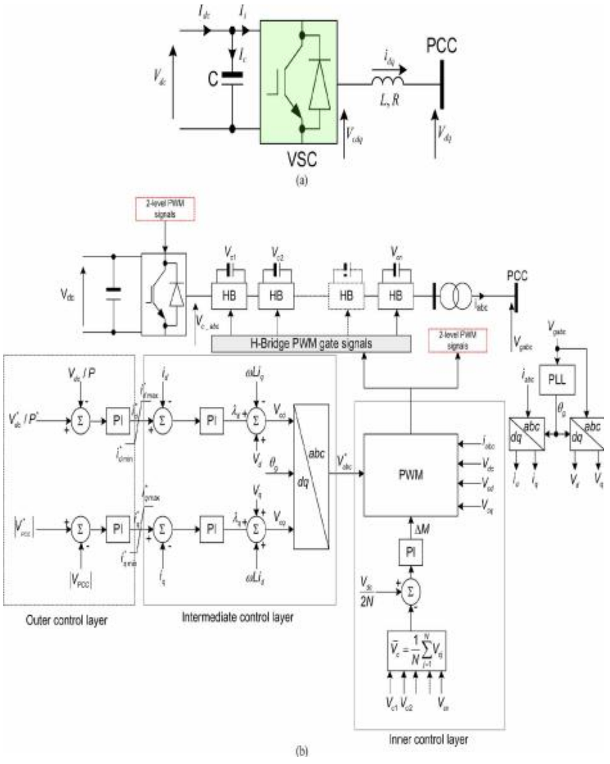


Fig. 2 shows one phase of a hybrid multilever VSC with H-bridge cells per phase. It can generate voltage levels at converter terminal "a" relative to supply midpoint "0." Therefore, with a large number of cells per phase, the converter presents near pure sinusoidal voltage to the converter transformer as depicted in Fig. 1 [1]. The two-level converter that blocks high-voltage controls the fundamental voltage using selective harmonic elimination (SHE) with one notch per quarter cycle, as shown in Fig. 2. Therefore, the two-level converter devices operate with 150-Hz switching losses, hence low switching losses and audible noise are expected. The H-bridge cells between "M" and "a" are operated as a series active power filter to attenuate the voltage harmonics produced

ADAM *et al.*: NEW BREED OF NETWORK FAULT-TOLERANT VOLTAGE-SOURCE-CONVERTER HVDC TRANSMISSION SYSTEM 337 by the two-level converter bridge.

These H-bridge cells are controlled using level-shifted carrier-based multilevel pulse width modulation with a 1-kHz switching frequency. To minimize the conversion losses in the H-bridge cells, the number of cells is reduced such that the voltage across the H-bridge floating capacitors sum to .

This may result in a small converter station, because the number of H-bridge cells required per converter with the proposed HVDC system is one quarter of those required for a system based on the modular multilevel converter. With a large number of cells per phase, the voltage waveform generated across the H-bridge cells is as shown in Fig. 2, and an effective switching frequency per device of less than 150 Hz is possible. The dc fault reverse-blocking capability of the proposed HVDC system is achieved by inhibiting the gate signals to the converter switches, therefore no direct path exists between the ac and dc side through freewheel diodes, and cell capacitor voltages will oppose any current flow from one side to another. Consequently, with no current flows, there is no active and reactive power exchange between ac and dc side during dc-side faults. This dc fault aspect means transformer coupled H-bridges cannot be used.

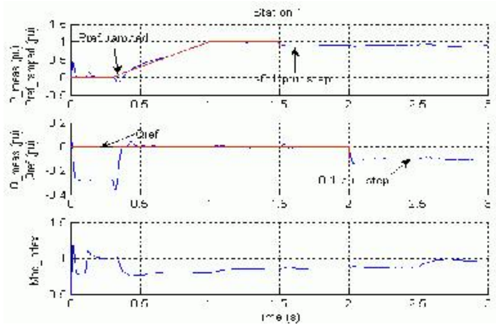
The ac grid contribution to dc-side fault current is eliminated, reducing the risk of converter failure due to increased current stresses in the switching devices during dc-side faults. From the grid standpoint, the dc fault reverse-blocking capability of the proposed HVDC system may improve ac network voltage stability, as the reactive power demand at converter stations during dc-side faults is significantly reduced. The ac networks see the nodes where the converter stations are connected as open circuit nodes during the entire dc fault period. However, operation of the hybrid multilevel VSC requires a voltage-balancing scheme that ensures that the voltages across the H-bridge cells are maintained at under all operating conditions, where is the total dc link voltage. The H-bridge cells voltage balancing scheme is realized by rotating the H-bridge cell capacitors, taking into account the voltage magnitude of each cell capacitor and phase current polarity. An additional PI regulator is used to ensure that the cell capacitors be maintained at as depicted in Fig. 2(b) (inner control lay

Converters 1 and 2	
Power ratings	687MVA
Maximum active power capability	600MW
Maximum reactive power capability	335MVAr
Two-level dc link voltage	600kV
H-bridge dc link voltage	42.86kV
Two-level dc link capacitance	150μF
H-bridge cell capacitance	3mF
H-bridge switching frequency	1kHz
Converter 1 controllers	
Current controller: K_p	35
Current controller: K_i	3000
Power controller: K_{pp}	0.0015
Power controller: K_{ip}	20
AC voltage controller: K_{pv}	30
AC voltage controller: K_{iv}	500
Converter 2 controllers	
Current controller: K_p	38
Current controller: K_i	2000
DC voltage controller: K_{pdc}	0.015
DC voltage controller: K_{idc}	0.0573
AC voltage controller: K_{pv}	0.00015
AC voltage controller: K_{iv}	400

Transformers 1 and 2	
Power rating	687MA
Voltage ratio	330kV/400kV
Per unit impedance	(0.0008+j0.32)

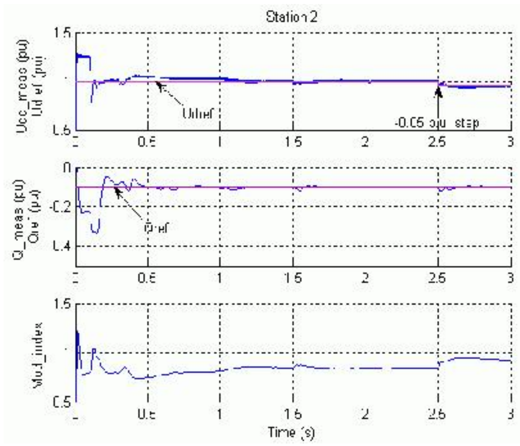
system Startup - Steady-State and Step Response

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

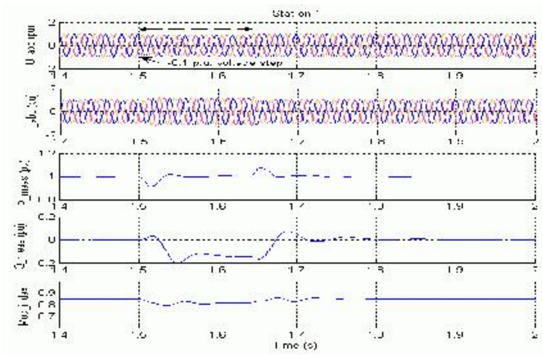


Station 2 converter controlling DC voltage is first deblocked at t=0.1 s. Then, station 1 controlling active power converter is deblocked at t=0.3 s and power is ramped up slowly to 1 pu. Steady state is reached at approximately t=1.3 s with DC voltage and power at 1.0 pu (200 kV, 200 MW). Both converters 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.

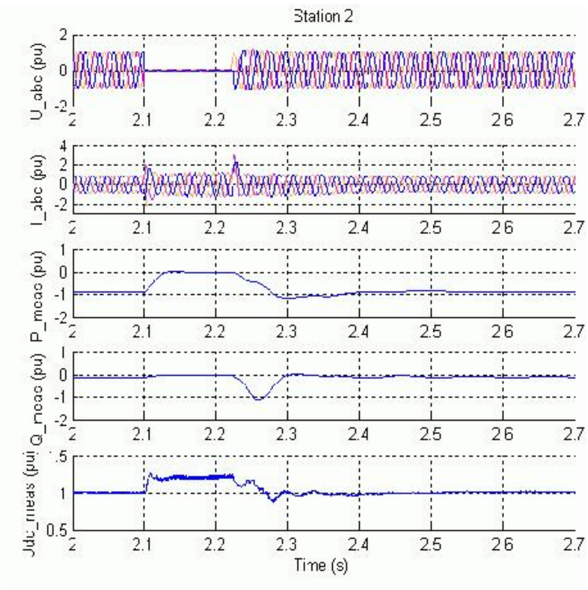
Voltage Step on AC System 1



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.

CONCLUSION

This paper presented a new generation VSC-HVDC transmission system based on a hybrid multilevel converter with ac-side cascaded H-bridge cells. The main advantages of the proposed HVDC system are:

•potential small footprint and lower semiconductor losses compared to present HVDC systems.

• low filtering requirements on the ac sides and presents high-quality voltage to the converter transformer.

•does not compromise the advantages of VSC-HVDC systems such as four-quadrant operation; voltage support capability; and black-start capability, which is vital for connection of weak ac networks with no generation and wind
farms.

•modular design and converter fault management (inclusion of redundant cells in each phase may allow the system to operate normally during failure of a few H-bridge cells; whence a cell bypass mechanism is required).

•resilient to ac side faults (symmetrical and asymmetrical).

•inherent dc fault reverse blocking capability that allows converter stations to block the power paths between the ac and dc sides during dc side faults (active power between ac and dc sides, and reactive power exchange between a converter station and ac networks), hence eliminating any grid contribution to the dc fault current

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