A New Network Proposal for Fault-Tolerant HVDC Transmission Systems

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Abstract: ***This paper proposes a new stock of high-voltage dc (HVDC) transmission systems based on a hybrid multilevel voltage source converter (VSC) with ac-side cascaded H-bridge cells. The proposed HVDC system offers the operational stretchability of VSC based systems in terms of active and reactive power control, black start capability, 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.***

Keywords: HVDC, Fault Tolerant, Stack of Network

1. Introduction

The VSC topology is a high power electronics technology used in electric power systems. The introduction of VSC made evolutionary changes in power transmission through HVDC network. Now HVDC transmission is an efficient and flexible method to transmit large amount of electric power over long distances by means of overhead transmission line or underground / submarine cables. It can also be used in order to interconnect asynchronous power systems.

In the last decade, VSC-HVDC transmission systems have evolved from simple two-level converters to neutral point clamped converters and then to multilevel converters such as a modular converter. These converter evolutions are aimed to lower semiconductor losses and increase the power handling capability of VSC-HVDC transmission systems to conventional HVDC systems based on thyristor current source converter. The other goals behind new evolutions are to improve ac side wave form quality in order to minimize or eliminate ac filters, reduce stresses in voltage on converter transformers and to decrease converter overall cost and footprint.

A VSC-HVDC transmission system is a candidate to meet these challenges due to its operational flexibility, such as provision of voltage support to ac networks, its ability to operate independent of ac network strength therefore makes it suitable for connection of weak ac networks such as offshore wind farms, suitability for multiterminal HVDC network realization as active power reversal is achieved without dc link voltage polarity change, and resiliency to ac side faults (no risk of commutation failure as with line-commutating HVDC systems).However, vulnerability to dc side faults and absence of reliable dc circuit breakers capable of operating at high-voltage restrict their application to point-to-point connection.

The magnitude of the dc-side capacitors' discharge current decays with time and is larger than the ac networks contribution. For this reason, dc fault interruption may require dc circuit breakers that can tolerate high let-through current that may flow in the dc side during the first few cycles after the fault, with high current breaking capacity and fast interruption time. Recent HVDC converter topologies with no common dc link capacitors, such as the modular multilevel converter (M2C), may minimize the magnitude and duration of the discharge current first peak.

This paper presents a new HVDC transmission systems based on a hybrid-voltage-source multilevel converter with ac-side cascaded H-bridge cells. The adopted converter has inherent dc fault reverse-blocking capability, which can be exploited to improve VSC-HVDC resiliency to dc side faults. With coordination between the HVDC converter station control functions, the dc fault reverse-blocking capability of the hybrid converter is exploited to achieve the following:

Eliminate the ac grid contribution to the dc fault, hence minimizing the risk of converter failure due to uncontrolled over current during dc faults.

Controlled recovery without interruption of the VSC-HVDC system from dc-side faults without the need for opening ac-side circuit breakers.

Simplify dc circuit breaker design due to a reduction in the magnitude and duration of the dc fault current.

Improve voltage stability of the ac networks as converter reactive power consumption is reduced during dc-side faults.

2. Cascaded Multilevel Converter

Consider a simple cascade multilevel converter with two H-bridges. To operate a cascade multilevel converter using a single DC source, it is proposed to use capacitors as the DC sources for all but the first source. The DC source for the first H-bridge (H1) is a DC power source with an output voltage of Vdc , while the DC source for the second H-bridge (H2) is a capacitor voltage to be held at Vdc / 2.The output voltage of the first H-bridge is denoted by v1 and the output of the second H-bridge is denoted by v2 so that the output of this two DC source cascade multilevel inverter is v (t) = v1 (t) + v2 (t). By opening and closing the switches of H1 appropriately, the output voltage v1 can be made equal to −Vdc, 0, or Vdc while the output voltage of H2 can be made equal to −Vdc/2, 0, or Vdc/2 by opening and closing its switches appropriately.

3. Hybrid Multilevel VSC with AC-Side Cascaded H-Bridge Cells

The Fig.1 shows single- phase of a hybrid multilevel VSC with N H-Bridge cells per phase. It can able to generate 4N+1 level at converter terminal "a" relative to supply midpoint "0". Therefore, with a large number of cells per phase, the converter will produce a pure sinusoidal voltage to the converter transformer.

The H-bridge cells between "M" and "a" are operated as a series active filter to attenuate the harmonics in voltage produced by two level converter bridge. In order 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 capacitor sum to Vdc/ 2. As a result of using less number of H-bridge cells, a small converter station is required than that of modular multilevel converter. Here a seven cell topology is used which will capable to provide 29 level voltage at converter terminal. The effective switching frequency per device is only less than 150 Hz. However the operation of hybrid multilevel VSC requires a voltage balancing scheme which ensures that the voltage across the H-bridge cells are maintained at Vdc/N under all operating conditions, where the Vdc is the total dc link voltage.

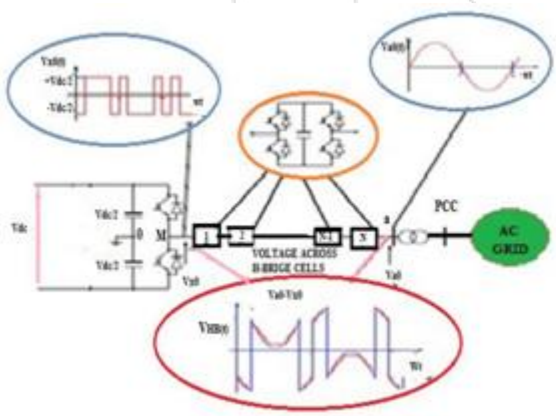

Figure 1: Single phase representation of a hybrid multilevel VSC with N H-Bridge cells per phase

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 V_{dc}/N 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.

4. Controlling Technique

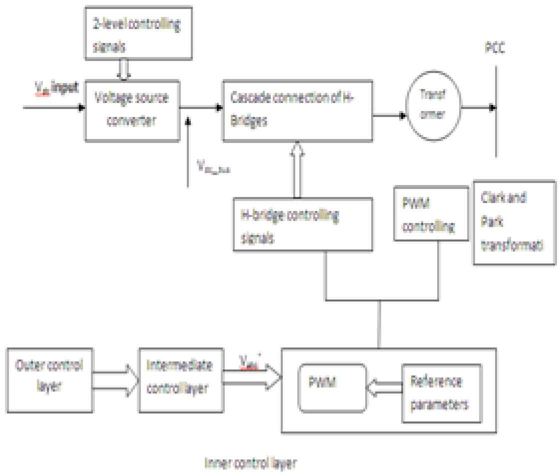

Figure 2: Schematic diagram summarizing the control layer of the hybrid multilevel converter with ac side cascaded H-bridge cells

A HVDC transmission system based on a hybrid multilevel VSC with ac-side cascaded H-bridge cells requires three control system layers. The inner control layer represents the modulator and capacitor voltage-balancing mechanism that generates the gating signals for the converter switches and maintains voltage balance of the H-bridge cell capacitors. The intermediate control layer represents the current controller that regulates the active and reactive current components over the full operating range and restraints converter station current injection into ac network during network disturbances such as ac and dc side faults. The outer control layer is the dc voltage (or active power) and ac voltage (or reactive power) controller that provide set points to the current controllers. The inner controller has only been discussed to a level appropriate to power systems engineers. The intermediate and outer control layers are presented in detail to give the reader a sense of HVDC control system complexity. The current, power, and dc link voltage controller gains are selected using root locus analysis, based on the applicable transfer functions. Some of the controller gains obtained using root locus analysis give good performance in steady state but failed to provide acceptable network disturbance performance. Therefore, the simulation final gains used are adjusted in the time domain to provide satisfactory performance over a wide operating range, including ac and dc side faults.

TABLE II
CONVERTER TRANSFORMER PARAMETERS

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

TABLE III
TRANSMISSION SYSTEMS PARAMETERS

Lines parameters (based on lumped π model)	
ac line length	60km
ac line series impedance	(0.0127+j0.2933)Ω/km
ac line shunt capacitance	12.74nF/km
dc transmission distance	75km
dc line series resistance	13.9mΩ/km
dc line series inductance	0.159mH/km
dc line shunt capacitance	0.231μF/km

5. AC Faults

During the fault period the power command to converter 1 is reduced in proportion to the reduction in the ac voltage magnitude (this is achieved by sensing PCC2 voltage). This is to minimize the two-level converter dc link voltage rise because of the trapped energy in the dc side, since power cannot be transferred as the voltage at PCC2 collapses.

Here in this topology an additional PI regulator is used to ensure that the cell capacitors are maintained at Vdc/N. Hence by considering voltage magnitude of each cell capacitor and phase current polarity, the H-bridge cells voltage balancing scheme can be realized in rotating the H-bridge cell capacitors.

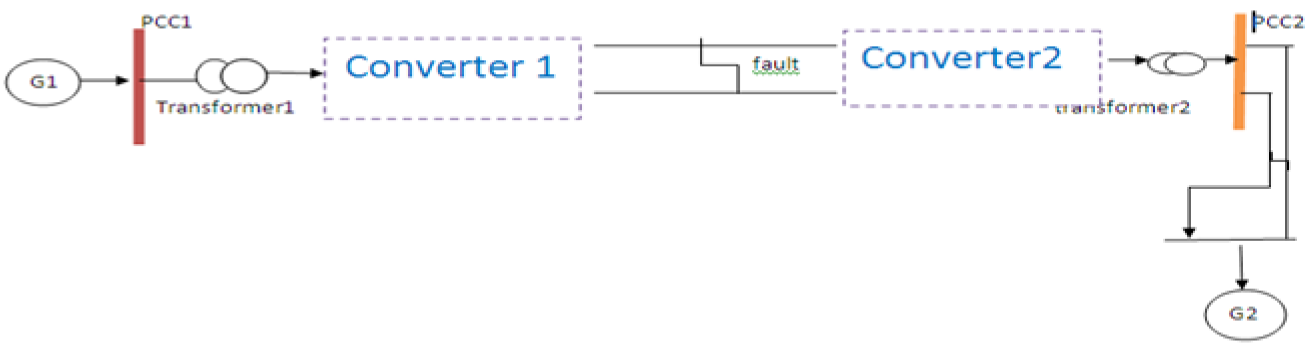

Figure 3: Test network used to illustrate the viability of the hybrid multilevel voltage source converter HVDC systems

6. DC Faults

The inherent current-limiting capability of the hybrid multilevel VSC with ac-side cascaded H-bridge cells that permits the VSC-HVDC system to ride-through dc-side faults will be demonstrated here. The test network is subjected to a 140 ms solid pole-to-pole dc-side fault at the location indicated .During the dc-side fault period, active power exchange between the two grids and is reduced to zero. This facilitates uninterruptable system recovery from the temporary dc fault with minimal inrush current, since the power paths between the converter’s ac and dc sides are blocked (by inhibiting all converter gate signals) to eliminate a grid contribution to the dc fault.

This contribution creates a noticeable reduction in the cell capacitor voltages during system restart. The cell capacitors of converter 2 that regulate dc link voltage, experience a larger voltage dip than converter 1, which regulates active power. However, the reduction in H-bridge cell capacitor voltages is minimized if large capacitance is used.

7. Simulation Analysis

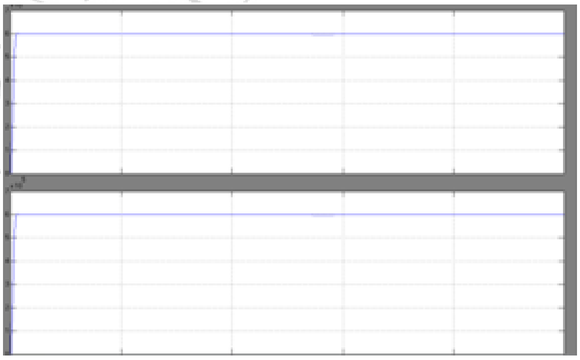

Figure 4: DC link voltages

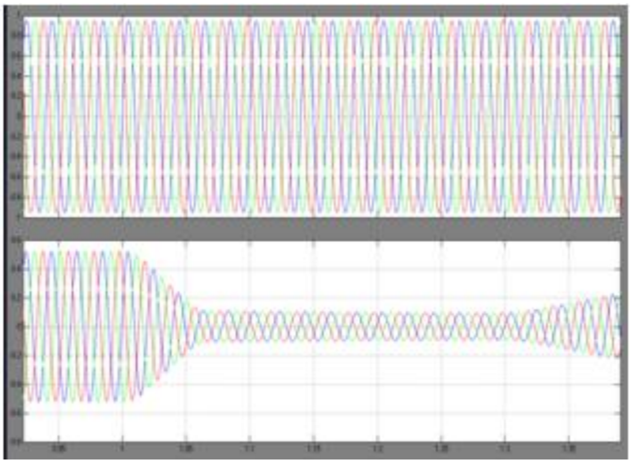

Figure 5: Voltage and current waveforms at PCC1

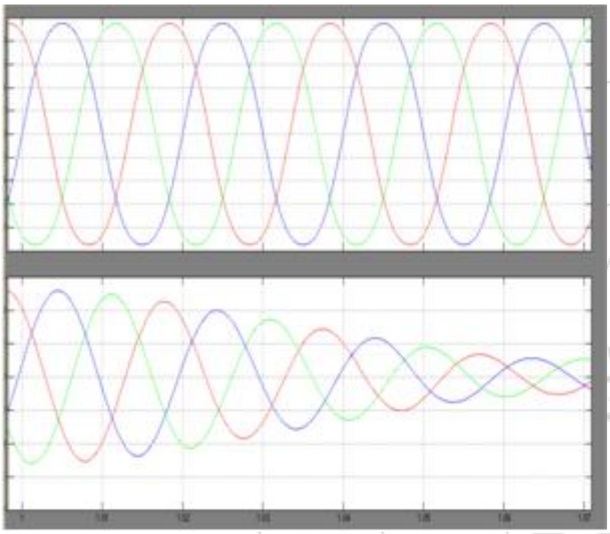

Figure 6: Voltage and current waveforms at PCC2

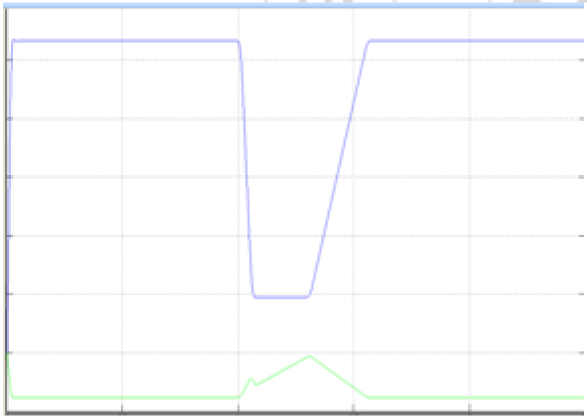

Figure 7: Active and reactive powers of PCC1

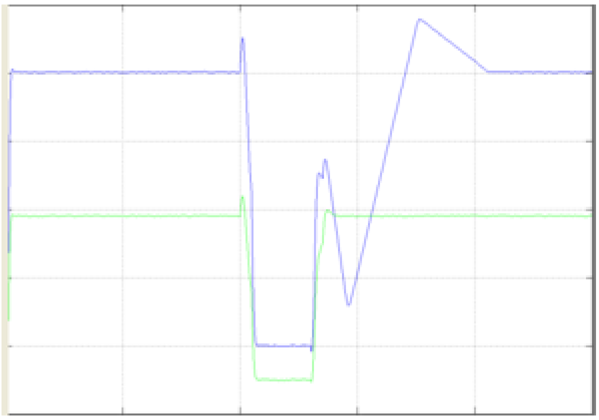

Figure 8: Active and reactive powers of PCC2

8. 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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