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New Breed of Network Fault-Tolerant Voltage Source Converter HVDC Transmission System

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Abstract: This paper proposes a new breed 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 flexibility 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Keywords: Historical Document Binarization, Phase-Derived Features, Ground Truthing, Document Enhancement.

I. INTRODUCTION

In 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 With increased demand for clean energy, power system networks need to be reengineered to be more efficient and flexible and reinforced to accommodate increased penetration of renewable power without compromising system operation and reliability. 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.

Present VSC-HVDC transmission systems rely on their converter station control systems and effective impedance between the point-of-common-coupling (PCC) and the converter terminals to ride-through dc side faults. With present converter technology, the dc fault current comprises the ac networks contribution through converter free-wheeling diodes and discharge currents of the dc side capacitors (dc link and cable distributed capacitors). 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. There are two approaches to assist VSC-HVDC transmission systems to ride-through dc side faults. The first approach is to use a fast acting dc circuit breaker, with considerably high let-through current to tolerate the high dc fault discharge current that may flow in the dc side. This breaker must be capable of operating at high voltage and isolates temporary or permanent dc faults, plus have a relatively high-current-breaking capacity. Reference presents a prototype 80-kV dc circuit breaker with dc current breaking capacity of 9 kA with in 2ms. However, this first step is inadequate, as the operating voltage of present VSC-HVDC transmission systems reach 640 kV pole-to-pole (or 320 kV for a bi-polar configuration), with power-handling capability of 1 GW.

This breaker approach may introduce significant steady-state losses due to the semiconductors in the main current path. The second approach is to use converter stations with dc fault reverse-blocking capability. Each converter station must be able to block current flow between the ac and dc sides during a dc fault, allowing dc-side capacitor discharge current, which is the major component of the dc fault current, to decay to zero and then isolate the fault. Several converter topologies with this inherent feature have been proposed, including an H-bridge modular multilevel converter, an alternative arm modular multilevel converter, and a hybrid multilevel converter with ac-side cascaded H-bridge cells as shown in Fig.1. However, the drawback is that the active power exchange between the ac networks reduces to zero during the dc fault period. Commensurate with the second approach, this paper presents a new HVDC transmission systems based on a hybrid-voltage-source multilevel converter with ac-side cascaded H-bridge cells.

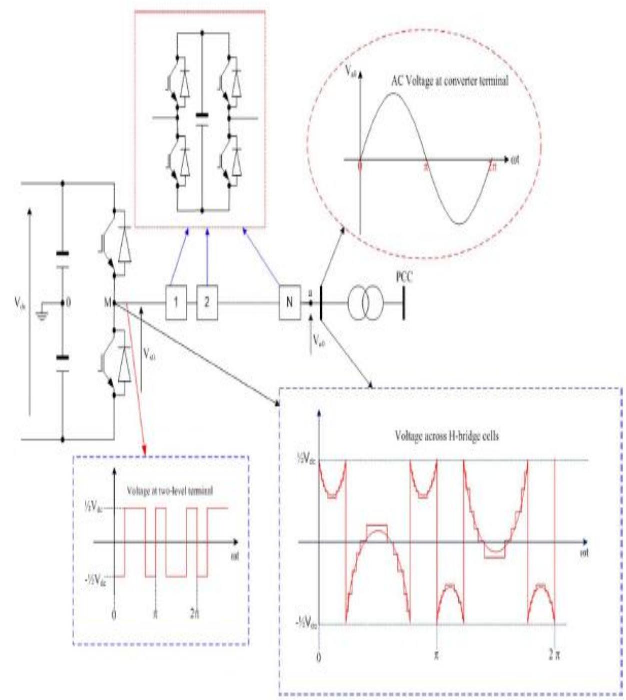


Fig.1. Hybrid voltage multilevel converter with ac side cascaded H-bridge cells.

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 facilitate 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; and improve voltage stability of the ac networks as converter reactive power consumption is reduced during dc-side faults.
- Section II of this paper describes the operational principle and control of the hybrid voltage source multilevel converter with ac-side cascaded H-bridge cells.
- Section III describes the HVDC system control design, specifically, ac current controller in synchronous reference frame, dc link voltage, and active power, and ac voltage controllers. A detailed block diagram that summarizes how different control layers of the proposed HVDC transmission system are interfaced is presented.
- Section IV presents simulations of a hybrid converter HVDC transmission system, which demonstrate its response during steady-steady and network disturbances. Included are simulations of four quadrant operation, voltage support capability, and ac and dc fault ride-through capabilities.

II. HYBRID MULTILEVEL VSC WITH AC-SIDE CASCADED H-BRIDGE CELL

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 The two-level converter that blocks high-voltage controls the fundamental voltage using selective harmonic elimination (SHE) with one notch per quarter cycle, 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 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 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

III. CONTROL SYSTEMS

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. Fig. 2 summarizes the control layers of the hybrid multilevel VSC. Current Controller Design: The differential equations describing the ac-side transient and steady-state are

$$\frac{di_d}{dt} = -\frac{R}{L}i_d + \frac{1}{L}(V_{cd} - V_d + \omega L i_q) \tag{1}$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q + \frac{1}{L}(V_{cq} - V_q - \omega L i_d) \tag{2}$$

Assume

$$\lambda_d = V_{cd} - V_d + \omega L i_q \quad \text{and} \quad \lambda_q = V_{cq} - V_q - \omega L i_d$$

$$\frac{di_d}{dt} = -\frac{R}{L}i_d + \frac{1}{L}\lambda_d \tag{3}$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q + \frac{1}{L}\lambda_q. \tag{4}$$

The new control variables and can be obtained from two proportion-integral controllers (PI) having the same gains:

$$\lambda_d = K_p\left(i_d^* - i_d\right) + K_i \int \left(i_d^* - i_d\right) dt \tag{5}$$

$$\lambda_q = K_p\left(i_q^* - i_q\right) + K_i \int \left(i_q^* - i_q\right) dt \tag{6}$$

Where and represent reference direct and quadrature current components. To facilitate control design in state space, the integral parts of and are replaced by and , rearranged in the following form:

$$\lambda_d = K_p\left(i_d^* - i_d\right) + W_d \tag{7}$$

$$\lambda_q = K_p\left(i_q^* - i_q\right) + W_q. \tag{8}$$

The integral parts, in differential equations form, are

$$\frac{dW_d}{dt} = -K_i i_d + K_i i_d^* \tag{9}$$

$$\frac{dW_q}{dt} = -K_i i_q + K_i i_q^*. \tag{10}$$

After substitution of (7) and (8) into (3) and (4), two identical and independent sets of equations, suitable for control design, are obtained as

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{dW_d}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{(R+K_p)}{L} & \frac{1}{L} \\ -K_i & 0 \end{bmatrix} \begin{bmatrix} i_d \\ W_d \end{bmatrix} + \begin{bmatrix} \frac{K_p}{L} \\ K_i \end{bmatrix} i_d^* \tag{11}$$

$$\begin{bmatrix} \frac{di_q}{dt} \\ \frac{dW_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{(R+K_p)}{L} & \frac{1}{L} \\ -K_i & 0 \end{bmatrix} \begin{bmatrix} i_q \\ W_q \end{bmatrix} + \begin{bmatrix} \frac{K_p}{L} \\ K_i \end{bmatrix} i_q^*. \tag{12}$$

After Laplace manipulations of the state-space equations in , one transfer function is obtained for and , which is used for the current controller design

$$\frac{i_d(s)}{i_d^*(s)} = \frac{i_q(s)}{i_q^*(s)} = \frac{\frac{K_p}{L}s + \frac{K_i}{L}}{s^2 + \frac{(R+K_p)}{L}s + \frac{K_i}{L}}.$$

Equations relating the reference voltages to the modulator and , current controller output, and feed forward terms can be obtained from expressions for and as follows

$$V_{cd}^* = \lambda_d + V_d - \omega L i_q \tag{13}$$

$$V_{cq}^* = \lambda_q + V_q + \omega L i_d. \tag{14}$$

Based on (5), (6), (13), and (14), the structure of the current controller (intermediate layer) is obtained. DC Voltage Controller: the differential equation describing the converter dc-side dynamics is

$$C\frac{dv_{\rm dc}}{dt} = I_{\rm dc} - I_i. \tag{15}$$

Assuming a lossless VSC, dc power at the converter dc link must equal the ac power at converter terminal Therefore, (15) can be written as

$$C\frac{dV_{dc}}{dt} = I_{\rm dc} - \frac{(V_{cd}i_d + V_{cq}i_q)}{V_{\rm dc}} \tag{16}$$

Equation (16) can be linearized using a Taylor series with the higher order terms neglected. Therefore, the linearized form of (16) is

$$\frac{d\Delta V_{\rm dc}}{dt} = \frac{\Delta I_{\rm dc}}{C} - \frac{V_{cd}}{CV_{\rm dc}}\Delta i_d - \frac{V_{cq}}{CV_{\rm dc}}\Delta i_q - \frac{i_d}{CV_{\rm dc}}\Delta V_{cd}$$

$$- \frac{i_q}{CV_{\rm dc}}\Delta V_{cq} + \frac{(V_{cd}i_d + V_{cq}i_q)}{CV_{\rm dc}^2}\Delta V_{\rm dc}. \tag{17}$$

Let $P_{\rm ac} = V_{cd}i_d + V_{cq}i_q$ and

$$\Delta u_{\rm dc} = \Delta I_{\rm dc} - (V_{cd}/V_{\rm dc})\Delta i_d - (V_{cq}/V_{\rm dc})\Delta i_q - (i_d/V_{\rm dc})\Delta V_{cd} - (i_q/V_{\rm dc})\Delta V_{cq}$$

and the variable $\Delta u_{\rm dc}$ can be obtained from the DC voltage controller based on the PI control as follows:

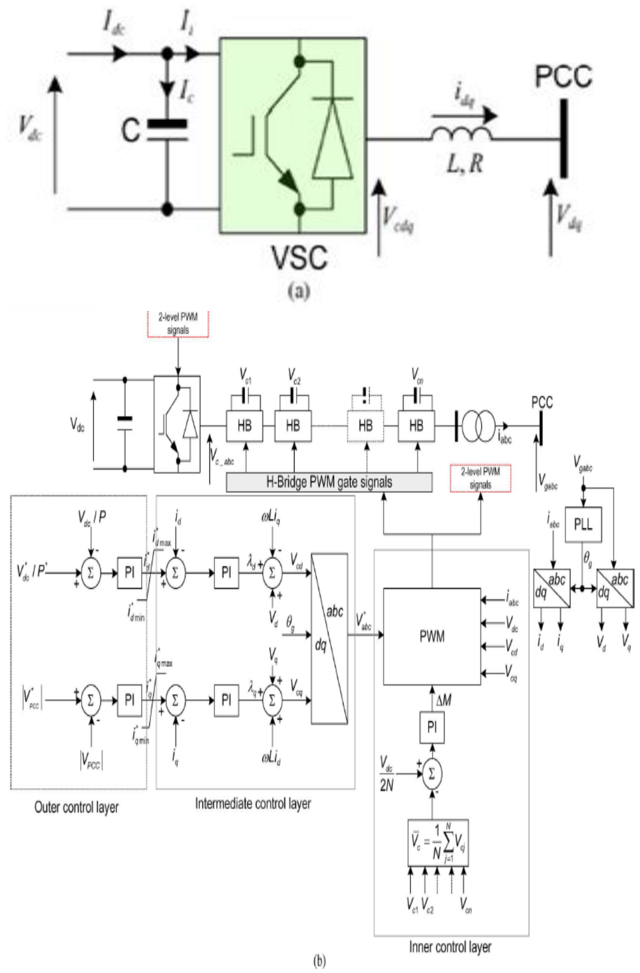


Fig.2. (a) Representation of VSC station and (b) schematic diagram summarizing the control layer of the hybrid multilevel converter with ac side cascaded H-bridge cells.

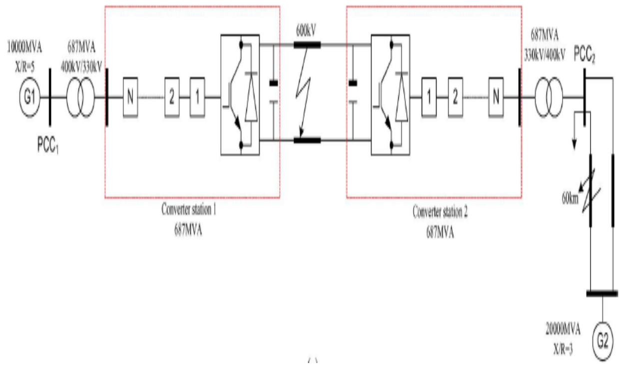
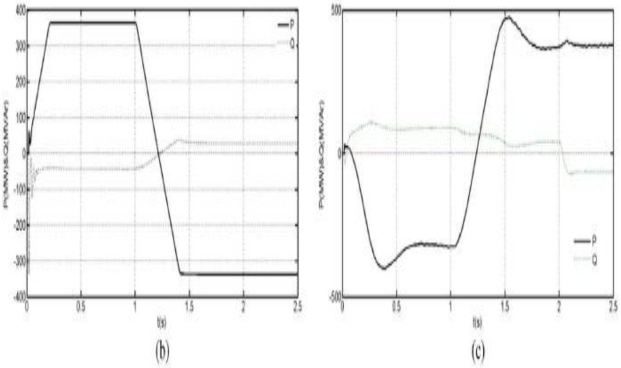


Fig.3.



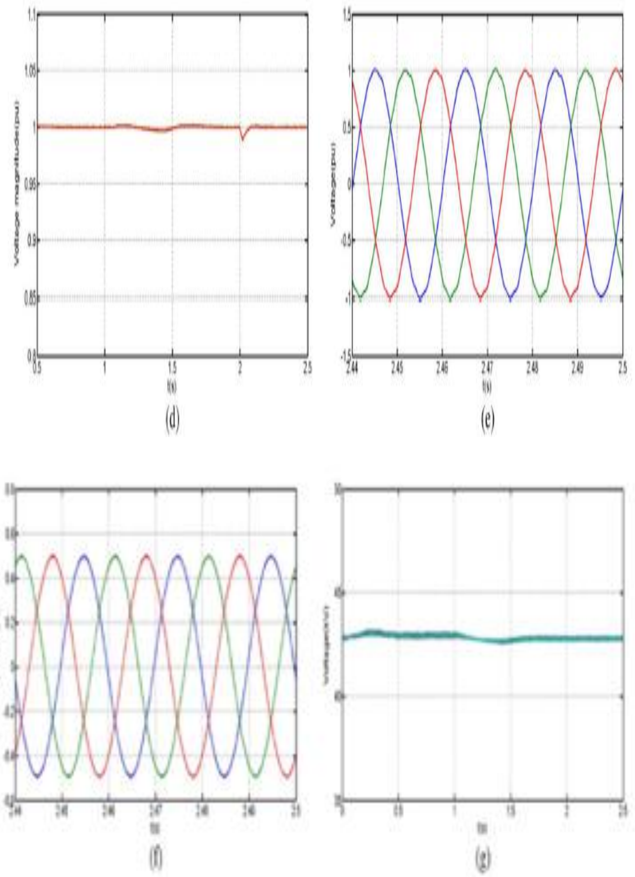
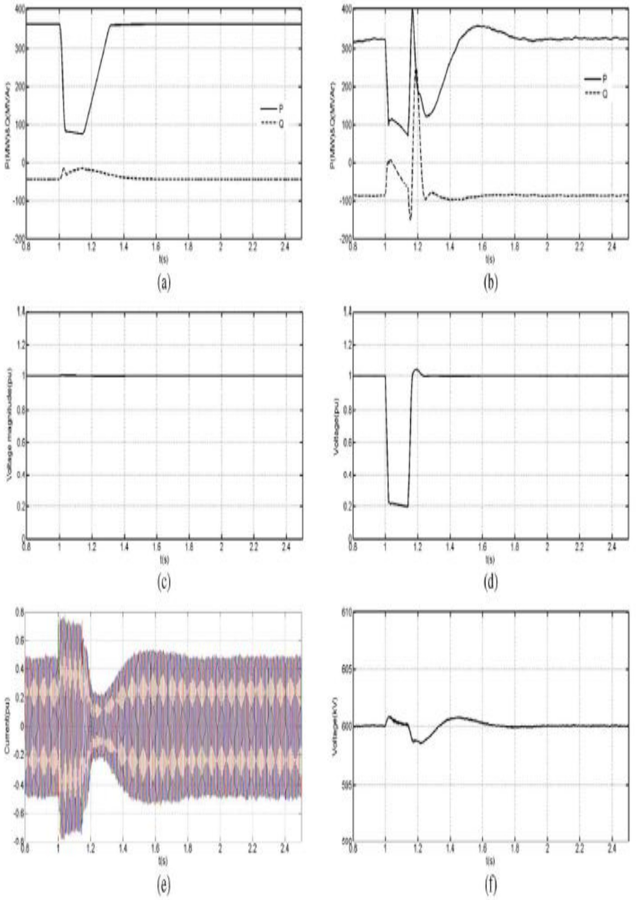
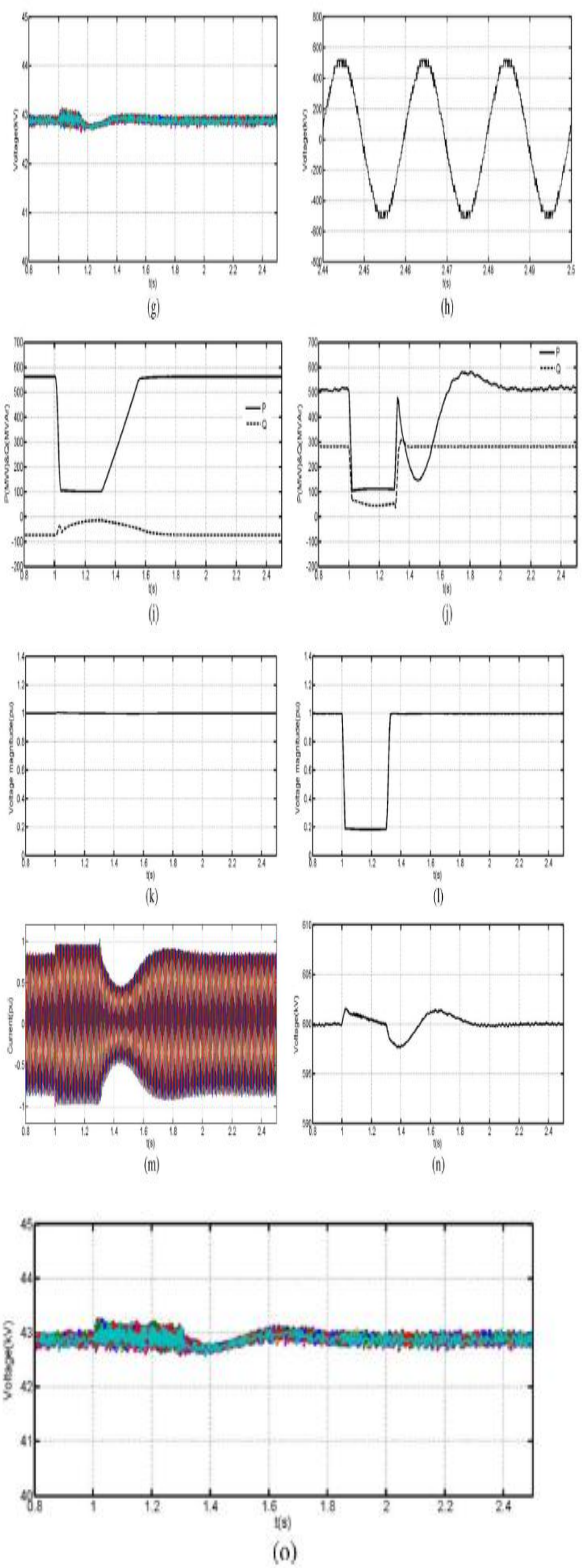


Fig.4.





(g) (h)

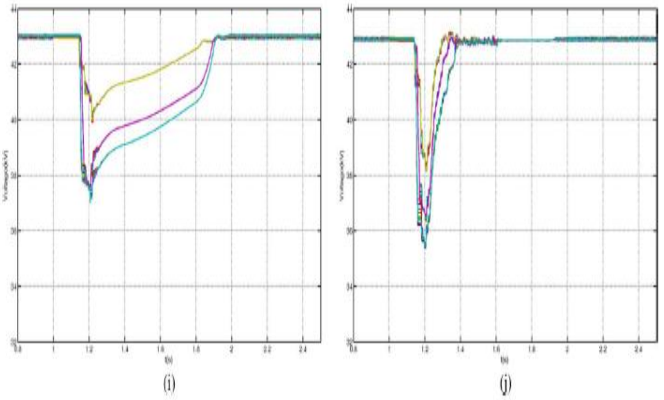
(i) (j)

(k) (l)

(m) (n)

(o)

Fig.5. (Continued.) Waveforms demonstrating ac fault ride-through capability of HVDC transmission systems based on hybrid voltage multilevel converter with ac side cascaded H-bridge cells. (k) Voltage magnitude at PCC1. (l) Voltage magnitude at PCC2. (m) Current waveforms converter 2 injects into PCC2. (n) Converter 2 dc link voltage. (o) Voltage across the 21 H-bridge cell capacitors of converter 2. Results in (i)–(o) demonstrate the case when the converter stations operate close to their maximum active power capabilities (power command at converter 1 is set to 0.75 pu, which is 515 MW) and system is subjected to a three-phase fault with a 300-ms duration.



(i) (j)

Fig.6.

V. 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 faultmanagement (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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