H-BRIDGE MODULAR MULTILEVEL CONVERTER (M2C) FOR HIGH-VOLTAGE APPLICATIONS

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ABSTRACT

This paper explores the steady-state and transient performance of the H-bridge modular multilevel converter in high-voltage dc transmission systems. Therefore the converter is simulated as one station of a voltage source converter HVDC transmission system. Steady-state performance investigation focuses on the converters ability to manipulate its active and reactive output power so as to control the ac voltage at the point of common coupling. To examine the H-bridge M2C resilience to large disturbances, the converter station is subjected to ac and dc side faults.

INTRODUCTION

The voltage source modular multilevel converter (M2C) that uses H-bridge cells instead of half cells has recently received attention from the industry and researchers [1]-[6]. The use of H-bridge cells in the converter arms introduce new sets of redundant switch states in the phase voltage that allow correction of any voltage imbalance in the cell capacitor voltages at any instant within one full fundamental cycle, independent of phase current polarity. This may contribute to reduced cell capacitor size without compromising system performance, thus giving a small converter footprint. The modular multilevel converter that uses H-bridge cells (see Fig. 1) has a unique feature of the dc fault reverse blocking capability (ability to block the power path from the ac to the dc side, hence no current flow in the converter switches)[4],[5]. This feature may permit the use of relatively slow dc circuit breakers with relatively low current breaking capacity to isolate permanent dc side faults. In addition, it may facilitate the practical realization of multi-terminal HVDC systems based on voltage converter technology. The major shortcoming of the H-bridge modular converter is that it suffers from high conversion losses (on-state and switching losses) as the number of devices in conduction path is twice that of the half cell M2C.

This paper describes operation, modulation and cell capacitor voltage balancing of the full H-bridge M2C in brief. Most of the discussion is focused on the steady-state and transient behaviour of the converter when connected to the grid. Therefore, the converter will be simulated as one-station of the voltage source converter high-voltage dc (VSC-HVDC) transmission system, with four cells per arm, controlled using sinusoidal pulse width modulation with triplen harmonic injection. The converter station is equipped with current, ac voltage and active power controllers. In steady-state, the converter station real and reactive power capabilities are examined according to the P-Q diagram from one of the main manufacturers of HVDC systems, and includes active power reversal. The transient performance of the H-bridge modular multilevel converter is examined by subjecting the system to ac faults (symmetrical three-phase fault) and dc faults (pole-to-pole dc side fault). The usefulness of the dc fault reverse blocking capability of the H-bridge modular multilevel converter, in the context of point-to-point and multi-terminal HVDC systems, and compliance with EMC requirements at point of common coupling, are highlighted.

H-BRIDGE M2C

Fig. 1 shows one-phase leg of the H-bridge M2C, with N cells per arm. The converter in Fig. 1 can generate $N+1$ voltage levels per phase. The voltage across each switching device is limited to one cell capacitor voltage. Proper operation of an H-bridge modular multilevel converter requires a robust capacitor voltage balancing strategy to ensure that the voltage across each cell capacitor is $\frac{1}{N}V_{dc}$. Modulation and capacitor voltage balancing of the H-bridge M2C is similar to that of the two-switch M2C, except the use of full bridges introduces new redundant switch states that allow the voltage balancing of the cell capacitors to be achieved faster than that in the two-switch M2C. Additionally, the use of full bridge cells instead of half bridge cells in the converter arms allow blocking of the power path between ac and dc sides; this may result in no current flow in the converter switches. This feature is exploited in this paper to achieve the following benefits:

- DC fault reverse blocking capability, which may reduce the risk of converter switch failure during a dc side fault as the grid contribution to the dc fault current is completely eliminated.
- Reduces the current rating of dc circuit breaker that will be required to isolate dc side faults.
- May allow recovery without interruption from temporary dc side faults. Also, may simplify the recovery strategy of multi-terminal HVDC system from dc side faults as the current in the dc side will decay to zero when all the converters block and distributed capacitors of the cable are fully discharge.

But the major drawbacks of the H-bridge M2C are high conversion losses and relatively large converter footprint as the voltage across each converter arm must summed to the full dc link.

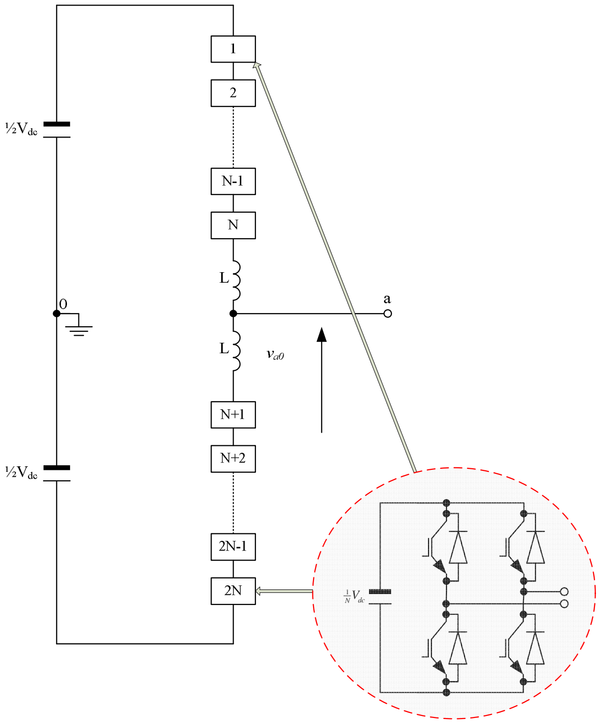

Fig. 1: One-phase of H-bridge M2C with N cells per arm

In an attempt to address these concerns, several derivatives of the H-bridge M2C have been proposed, such as alternative arm H-bridge M2C, and hybrid multilevel with two-level converter as the high-voltage stage and series connected H-bridge cells as the low voltage stage[4],[5]. The later version of the H-bridge M2C has potential to address both these concerns as it requires a minimum number of cell capacitors among all versions of modular multilevel converters. But because of limited space they will be not discussed in this paper.

TEST SYSTEM

Fig. 2 shows a 320kV dc 400MVA HVDC converter station based on the H-bridge M2C, connected to a 400kV ac network G_1 through a 132kV/400kV transformer and short transmission line. Test system details are depicted in Fig. 2. The converter station is modelled with the H-bridge M2C having four cells per arm and controlled using third harmonic injection pulse width modulation with a 2.1kHz carrier frequency. Each H-bridge cell uses a 6mF capacitor and no reservoir capacitor is connected across converter dc link. The converter station is equipped with active power, ac voltage and current controllers. The converter ac voltage controller regulates the voltage magnitude at B_1.

SIMULATIONS

This section investigates the suitability of the H-bridge modular multilevel converter in high-voltage applications. The investigation focuses on the steady-state and transient performance of the H-bridge modular multilevel converter when operated as a HVDC converter station. The transient performance investigation focuses on converter resiliency to ac and dc faults.

Steady-state performance Assessment

To assess the steady-state performance of the H-bridge M2C, the converter station is commanded to gradually increase its active power import from 0 to -0.5pu (-200MW) from the ac network G_1. At t = 1s the active power converter station exchange with bus B_1 is reduce to zero with a 0.5pu/s slope. While the converter output active power remains at zero, it continues to regulate the ac voltage at B_1 as a static synchronous shunt compensator (STATCOM). At t = 2s converter active power exchange with B_1 is increased such that it exports 200MW to G_1. At t = 3s, a load of 80MW and 60MVAr inductive is connected to B_1. Fig. 3 shows the results obtained. It can be observed that the converter station maintains tight control over active power and ac voltage magnitude at B_1 over the entire simulation period, with high quality voltage and current waveforms injected into the ac side at the point of common coupling. It can be noticed that the converter station adjusts its reactive power output as the loading at B_1 varies so as to maintain a constant voltage magnitude at B_1.

AC fault ride-through capability assessment

The resiliency of the H-bridge M2C is tested by subjecting the system in Fig. 2 to a solid three-phase fault at point F_1. The fault is initiated at t = 1.4s and cleared at t = 1.6s. During the fault period, converter active power output is reduced to zero to minimize the trapped energy in the dc side thus minimizing the dc link voltage rise. Fig. 4 shows the results obtained during a three-phase fault. The converter station recovers from the three-phase fault with the current controller successfully limiting the current contribution to the fault during the entire fault period despite the voltage magnitude at B_1 collapsing to zero. Also the voltage stress across converter switches is fully controlled as the voltages across the cell capacitors remain tight around the desire set-point.

DC fault ride through capability assessment

The resiliency of the H-bridge M2C to a dc side faults is tested by subjecting the system in Fig. 2 to a solid pole-to-pole dc side fault at point F_2. During the fault period the converter station output active power is reduced to zero and converter reverse blocking capability is activated by inhibiting the gate signals to the converter switches. The gate signals to converter switches are restored when the fault is cleared at t = 1.6s and is followed by a gradual increase in converter output active power, as shown in Fig. 5. During the entire fault period, the active and reactive power exchange with the grid are blocked, resulting in zero current in the converter switches. This confirms the ability of the H-bridge M2C to eliminate the grid contribution to the dc fault current as expected, hence reduces the risk of over-current in converter switches. As a result a dc circuit breaker with a relatively low current rating may be sufficient to isolate dc side faults.

CONCLUSIONS

This paper investigated the viability of a H-bridge modular multilevel converter in high-voltage applications, with emphasis on HVDC transmission systems. H-bridge M2C operating principle, modulation and capacitor voltage balancing were described. H-bridge M2C steady-state and transient performance were examined. It can be concluded that despite the H-bridge M2C increased semiconductor losses, the feature of dc fault reverse blocking capability is valuable and may facilitate the expansion of voltage source converter HVDC systems to multi-terminal configurations as the recovery from dc side fault is no longer an obstacle or is greatly simplified.

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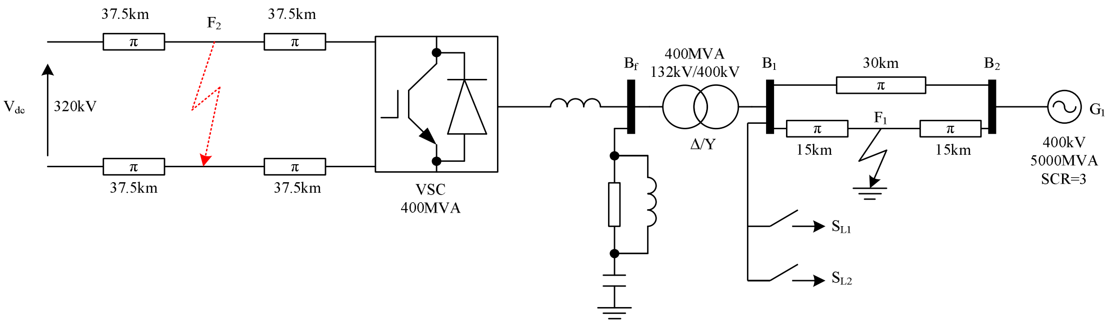
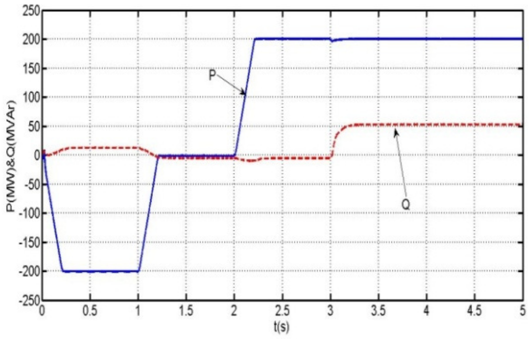
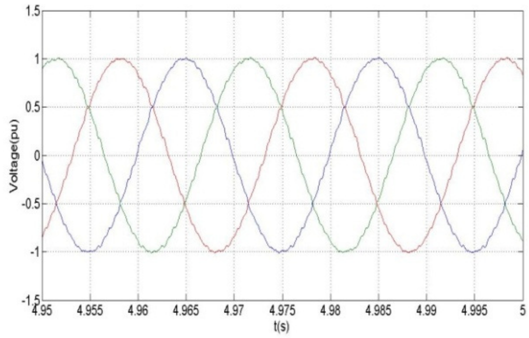


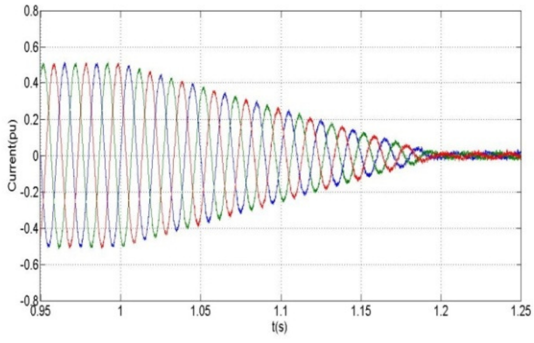
Fig. 2: Test system



(a) Active and reactive power at bus B1

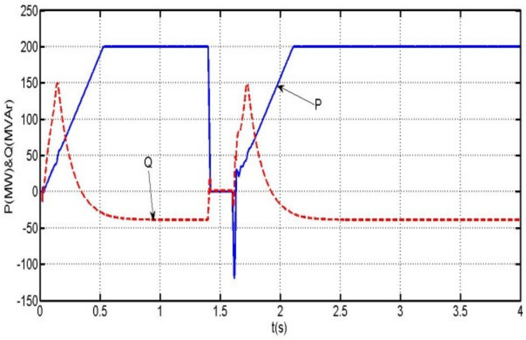


(b) Voltage waveforms at bus B_1

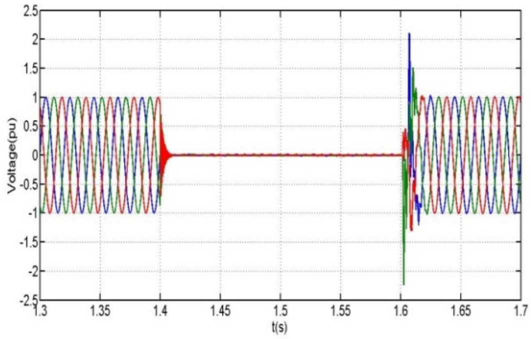


(c) Zoomed version of the current waveforms converter station injects into B_1 during the transition from active power importing mode to STATCOM mode

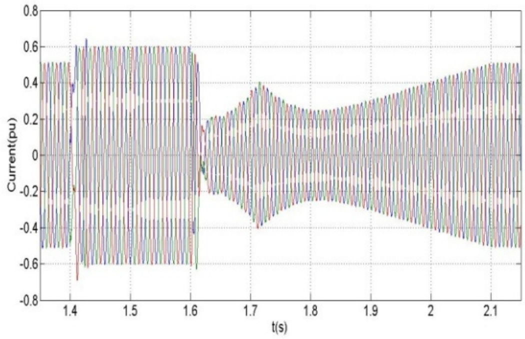
Fig. 3: Waveforms demonstrating steady-state performance of H-bridge M2C converter, including active power manipulation and voltage support capability.



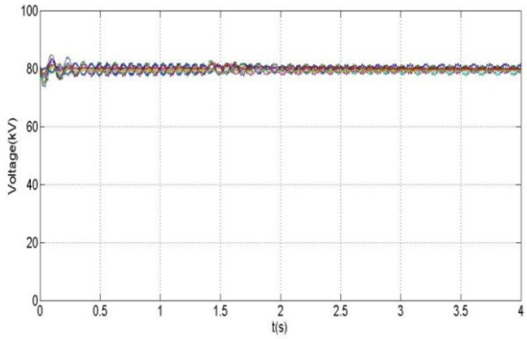
(a) Active and reactive power converter injects into bus B_1



(b) Voltage waveforms at bus B1

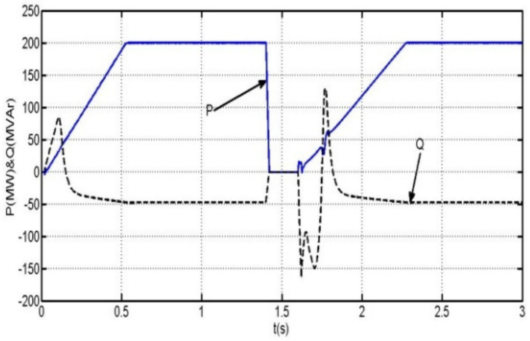


(c) Current waveforms H-bridge M2C station injects into

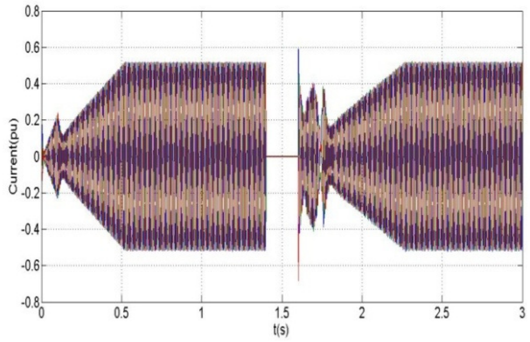


(d) Voltages across the 24 cell capacitors of the three-phase H-bridge M2C station

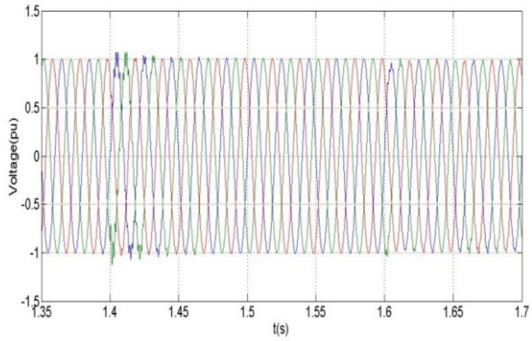
Fig. 4: Waveforms demonstrating the resiliency of the H-bridge cells M2C to a three-phase fault at F_1



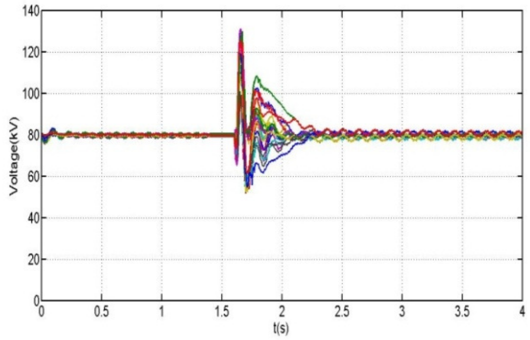
(a) Active and reactive power at bus B1



(b) Current waveforms H-bridge M2C injects into the low voltage side of the interfacing transformer (converter side)



(c) Voltage waveforms at B1



(d) Voltage across the 24 capacitors of the three-phase H-bridge M2C station

Fig. 5: Waveforms demonstrating the resiliency of the H-bridge M2C to pole-to-pole dc side fault