Interoperability of Different Voltage Source Converter Topologies in HVDC Grids

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Keywords: Interoperability; Voltage source converter; HVDC transmission systems; modular and hybrid multilevel converters; multi-terminal DC grids; offline and real-time simulations.

Abstract
This paper presents a detailed study of DC grid operation using a range of user-defined offline and real-time HVDC converter models which were rigorously validated against offline and real-time benchmarks. Provided that these models are destined for use in real-time hardware in the loop simulation and a wide range of offline system studies, this paper assesses their suitability for studying complex DC grids that consist of multiple voltage source converters which differ in their control range and fault ride-through capabilities. Detailed quantitative studies show that the offline and real-time DC grid models produce well matched results and provide efficient approaches to investigate DC grid operation during normal condition and AC and DC faults.

1 Introduction
In the last decade, a number of multilevel voltage source converters have been proposed for HVDC applications. Half-bridge (HB) and full-bridge (FB) modular multilevel converters (MMC) have emerged as the preferred topologies for commercial application to multi-terminal HVDC grids. In the meantime, several hybrid converters have been proposed as alternatives that offer important trade-offs between footprint, semiconductor loss, resiliency to AC and DC network faults and control range. Some of these hybrid converters are becoming increasingly attractive as they offer bespoke features, ranging from that of the HB-MMC to the FB-MMC.

Although the construction of large-scale DC grids using different converter topologies is important from both practical and market point of view, particularly for prevention of monopoly in supply chains, ensuring safe and reliable operation of DC grids with such diversity, present significant technical challenges; especially, during fault conditions.

Meaningful assessments of the interoperability of such complex DC grids, with equipment supplied by multiple vendors, require converter models with steady-state and transient behaviours that accurately resemble the typical behaviour of physical systems. All converter terminals (regardless of their topologies) must be designed to ensure that their steady-state and transient responses are confined within narrow band and with defined settling and rise times, maximum overshoots, permissible oscillating frequency, and damping in order to avoid undesirable interactions between converters.

With regard to modelling, concerted efforts from academia and industry in the last decade have resulted in development of universal modelling frameworks for MMC and hybrid converters, namely, Thevenin equivalent model which was initially developed in 1969 by Dommel in [1] and then extended to MMC in [2, 3], generalized switching function model [4-6], and averaged model [7, 8]. Detailed studies presented in [3, 6, 9-13] confirm that all the aforementioned models are capable of reproducing the typical behaviours of modular and hybrid converters during normal operation, and AC and DC faults.

Equally, the control of MMC and hybrid converters is extensively investigated in the last decade [14-22]. There are two common methods for controlling MMC and hybrid converters. The first method only manipulates the phase and magnitude of the AC voltage component for each phase-leg relative to that of AC grid as that in the two-level converter, with the DC components of the phase-legs fixed. The second method manipulates both AC and DC components of each phase leg to control active and reactive powers, and to decouple capacitor voltage regulation and dynamics from that of the DC link voltage.

The second control method allows the HB-MMC to control its DC link independent of the cell capacitor voltages and vary its DC link voltage and retain control as long as the DC voltage remains above the peak of the line-to-line voltage being imposed by the AC grid at its AC terminals. It permits FB-MMC to offer maximum control range in addition to DC fault blocking, i.e., controlled operation over wide range of positive and negative DC link voltages. Similarly, besides the DC fault blocking, hybrid MMC with 50% FB cells and 50% HB offers controlled operation between zero to rated positive DC link voltage.

Because of numerous mismatches between the attributes and capabilities of the voltage source converters briefly highlighted earlier, this paper examines the suitability of the offline and real-time converters’ models being developed in this study for detailed assessment of interoperability of different converters in a meshed DC grid. Interoperability of a few selected
representative converter topologies, namely, the HB and FB MMCs and hybrid MMC consisting of 50% FB cells and 50% HB will be assessed quantitatively using offline PSCAD and real-time RSCAD simulations. This study models all converter terminals using validated averaged models against their switching function equivalents in PSCAD and RSCAD with all main and auxiliary controllers incorporated [11].

Fig. 1: Basic circuit of three-phase modular multilevel converter

2 Converters modelling and control

2.1 Modelling

Fig. 1 shows a generic power circuit of a three-phase MMC converter. It consists of six arms, with each arm comprising of an inductor and a circuit link of HB or FB cells, or combination of the HB and FB cells. Fig. 2(a) shows generic phase legs of the HB and FB MMCs and of the hybrid MMC. The upper and lower arm voltages ($V_{armU}$ and $V_{armL}$) of the converters in Fig. 1 can be approximated as:

\[
V_{armU} \approx \frac{1}{2} V_{armL} [\alpha - \sin(\alpha + \delta)] \approx V_{armL} m_U
\]

\[
V_{armL} \approx \frac{1}{2} V_{armU} [\alpha + \sin(\alpha + \delta)] \approx V_{armU} m_L
\]

where $V_{armU}$ and $V_{armL}$ are the sums of the upper and lower arm capacitor voltages, and must be regulated such that

\[
V_{armU} = V_{armL} = V_{arm} \geq V_c \quad (V_{arm} \text{ is the rated arm capacitor voltage),}
\]

$\alpha$ is the DC modulation index defined as $\alpha = \frac{V_{dc}}{V_{rms}}$, $m_U$ and $m_L$ are the upper and lower arms modulation functions, respectively. For HB and FB MMCs, DC modulation indexes ‘$\alpha$’ vary narrowly around 1 and $-1 \leq \alpha \leq 1$, respectively. Fig. 2 (b) and (c) depict per arm averaged models of the half-bridge and full-bridge MMCs [7, 11, 23, 24], where the equivalent upper and lower arm capacitor currents $i_{capU}$ and $i_{capL}$ are:

\[
i_{capU} \approx \frac{1}{2} i_{armU} [\alpha - \sin(\alpha + \delta)] \approx i_{armL} m_U
\]

\[
i_{capL} \approx \frac{1}{2} i_{armL} [\alpha + \sin(\alpha + \delta)] \approx i_{armU} m_L
\]

Realization of blocking state in HB-MMC model in Fig. 2 (b) is achieved by adding the auxiliary devices $S_1$ and $D_1$ [11]. In FB-MMC model in Fig. 2 (c), blocking state is realized by gating off the insulated gate bipolar transistors (IGBTs) $S_1$, $S_2$, $S_3$ and $S_4$, and setting the upper and lower arm modulation functions $m_U = m_L = I$. The upper and lower arm voltages during de-block state are realized as:

\[
V_{armU} \approx V_{armL} \approx m_U
\]

\[
V_{armL} \approx V_{armU} \approx m_L
\]

In addition, when $\text{sign}(m_U) \geq 0$ the switches $S_1$ and $S_2$ are turned on and $S_3$ and $S_4$ are turned off, and the opposite is true for $\text{sign}(m_U) < 0$. The former scenario arises when FB-MMC arm synchronizes positive voltages, and latter scenario when the FB-MMC arm synchronizes negative voltages. The hybrid MMC facilitates normal and reduced DC link voltage operation and active control of DC fault current during pole-to-pole DC fault (zero DC voltage) by inserting the same number of cell capacitors with positive and negative polarities as that of the FB-MMC. Thus, provided that the HB and FB cells of the hybrid MMC have same capacitances, insertion of the FB cell capacitors with positive polarities will exhibit the same behaviours at cell and arm levels as that of the HB cells. This fact justifies the use of per arm averaged model depicted in Fig. 2(c) to represent the hybrid MMC (or mixed-cell MMC), provided the DC modulation control range is restricted as described above, and upper and lower arm modulation functions $m_U$ and $m_L$ are set to $\frac{1}{2}$ during converter blocking.

Fig. 2: Generic depictions of: (a) Phase-legs of half and full-bridge Modular and hybrid converters, (b) Enhanced per arm averaged model of the half-bridge MMC, (c) Enhanced per arm averaged model of full-bridge and hybrid MMC.
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2.2 Control system

Fig. 3 summarises the main and auxiliary controllers employed in this paper with HB, FB MMCs and hybrid MMC. The outer controllers on d-axis regulate active power or DC voltage and set the positive sequence d-axis current order. Likewise, the outer controllers on q-axis regulate reactive power or AC voltage and set the positive sequence q-axis current order. The inner current controllers regulate both positive and negative sequence currents and limit current contribution to AC fault and generate the AC components of the modulation functions. The negative sequence d- and q-axis current orders are set to zero to ensure balanced three-phase output currents during operation in unbalanced AC grids and asymmetric AC faults, but their orders can be set to other values if negative sequence current is required. Circulating current controller is implemented in each phase leg to suppress the 2nd order harmonic currents in the arms of the converters to reduce semiconductor power losses and cell capacitor voltage ripples. Horizontal and vertical cell capacitor voltage controllers are implemented to ensure equal voltage distribution across the three phase-legs of the converters and across the upper and lower arms of each phase leg. With averaged converter models adopted in this paper, each arm in Fig. 3 will be replaced by the averaged arms in Fig. 2 (b) or (c), depending on the converter topology to be simulated.

3 Test system

Fig. 4 shows an example test system being used to assess the interoperability of HB and FB MMCs and hybrid MMC in a generic DC grid. Converters T1, T2 and T3 are hybrid MMC, FB-MMC, and HB-MMC respectively. All converters are represented in PSCAD-EMTD and RTDS-RSCAD by their averaged models described in Section 2.1 and shown in Fig. 2 (b) and (c). The control system depicted in Fig. 3 is incorporated into each converter station. Simulation parameters of the test systems are shown in Fig. 4.

The DC grid shown in Fig. 4 is implemented in RTDS using the concept of multi-rate, with two distinct sampling times. The power circuits of the three converters and DC cables are placed in 3 processors on GPC cards that operate at 2.5μs time step. The three AC grids, control systems and part of the averaged model that calculates the capacitor voltage dynamics, operate at 50μs time step. Three AC sources that represent the AC grids and dynamics of the averaged model are placed in 2 processors on GPC card. The AC sides of the three converter models that operate at 2.5μs (small) time-steps are interfaced to the AC grids that operates at 50μs (large) time-step via three interfacing transformers. The DC side of the converter model and associated DC cable operate at small time-step but in different processors and are linked together through very short T-lines to form a DC grid.

It is worth emphasizing that the uses of T-lines for connecting converter models and DC cables that operate on different processors and the interfacing transformers for connecting system components that operate with different sample times have negligible impact on the accuracy of the real-time simulation, which will be demonstrated later.

4 Simulations

This section examines the use of the developed offline and real-time converter models described in Sections 2 and 2.2 to assess the performance of DC grid that consists of multiple converter topologies, considering normal operation and fault conditions.

4.1 Normal operation

Fig. 5 displays RSCAD simulation waveforms superimposed on their PSCAD equivalents, where PS and RT subscripts stand for PSCAD and RTDS simulations respectively. In the simulations of the DC grid in Fig. 4, converter T1 controls the DC grid voltage at 640kV, whilst T1 and T2 are operated as follows: at t=2s, T2 ramps its active power from 0 to 600MW at a rate of 1200MW/s; at t=2.5s, T1 ramps its active power output from 0 to 600MW at the same rate whereas within t=4-5s it reverses power from 600MW to -1000MW. Throughout this paper, converters T1, T2 and T3 maintain their reactive power outputs at zero.
The active power and DC voltage in Fig. 5 (a) and (b) show that the DC voltage controlling converter $T_1$ (HB-MMC) regulates its DC link voltage tightly around 640kV and adjust its active power exchange with the AC grid $G_3$ as the power controlling converters $T_1$ (hybrid MMC) and $T_3$ (FB-MMC) vary their active power set-points. These expected behaviours are replicated accurately by both the offline PSCAD and real-time RTDS simulation waveforms, see Fig. 5 (a) and (b).

**3.2 Three-phase-to-ground AC fault**

Fig. 6 shows real-time RTDS simulation waveforms superimposed on their PSCAD equivalents when the system is subjected to a 300ms temporary three-phase AC fault at converter $T_2$ AC terminal at $t=6s$. In the pre-fault condition, converters $T_1$ and $T_2$ control their active power outputs at 500MW and 600MW respectively, and converter $T_3$ maintains the DC grid voltage at 640kV.

Fig. 6 (a) shows the active powers of converters $T_1$, $T_2$ and $T_3$ measured at the grid sides of the transformers $B_1$, $B_2$ and $B_3$ respectively. The DC voltage shown in Fig. 6 (b) is briefly disturbed at the occurrence of the three-phase AC fault at $T_2$, which creates a temporary imbalance between AC and DC powers. The brief drop observed in the DC voltage is an indication of the deficit in the DC power as a result of a loss of the active power from the converter $T_2$, see Fig. 6 (a) - (c). During the fault, $T_2$ operates at current limit as seen in the arm and output phase currents displayed in Fig. 6 (d) and (e). Notice that the DC components of the arm current of $T_2$ drop to zero when its active power transfer capability collapses with the AC voltage at $B_2$ down to zero as shown in Fig. 6 (f). Since simulation waveforms displayed in Fig. 6 (a) through (f) show good agreement between the offline PSCAD and real-time RTDS models, and in line with broader theoretical understanding of DC grid behaviours during AC faults; it is concluded that both models are well-suited for AC fault studies of complex DC grids that employ different converter topologies.
4.3 Pole-to-pole DC short circuit fault
This section presents DC fault simulation waveforms when a permanent pole-to-pole DC short circuit is applied at the main DC fault node (F1) at t=4s and both converters T1 and T2 control their active powers at 600MW prior to the fault. All converters are blocked after 50µs after fault inception. Fig. 7 (a) and (b) show the pole-to-pole DC voltage at F1 and DC link currents of the three converters, with the DC link currents of the T1 (hybrid MMC) and T2 (FB-MMSC) drop to zero after the activation of the converters blocking, while T3 (HB-MMSC) continues to feed current into the DC fault through its AC supply. The plots in Fig. 7 (c) show the active powers of converters T1 and T2 drop to zero immediately after blocking, while T3 continues to draw reduced active power from AC grid G1 to feed the entire system losses during the DC fault. Similar behaviour can be observed from the DC current as Fig. 7 (d), (e) and (f) show the arm currents of T1 and T2 drop to zero and that of the T3 reverses direction and is fed from the AC side.

The DC voltages and currents, active powers and arm currents shown in Fig. 7 (a) through (f) are well matched between the offline and real-time simulation waveforms in terms of different dynamics and magnitudes during transients associated with the DC faults. Therefore, it is concluded that the presented models are well-suited for detailed DC fault studies in highly complex DC grids that consist of multiple voltage source converter topologies.

5 Conclusion
The rapid growth in the use of real-time hardware-in-the-loop simulation studies in order to facilitate extensive validations of the control and protection of HVDC systems in recent years have called for the development of rigorous models which are accurate and can be considered with high certainty as true representation of the physical systems. In response to this call, this paper has presented a summary of detailed quantitative study that assesses the interoperability of different converter topologies that operate side-by-side in a multi-terminal DC grid, with particular emphasis on the suitability of the models. Detailed examinations of the presented results, with the simulation waveforms of the real-time models superimposed on that of the offline PSCAD, reveal that both models being compared produce practically identical results during normal and abnormal conditions. On these bases, it has been concluded that the offline and real-time simulation models employed in this paper are well-suited for a wide range of DC grid studies such as normal operation, and AC and DC faults.

Acknowledgements
The project is sponsored by The National HVDC Centre.

References
This paper is a post-print of a paper submitted to and accepted for publication in The 15th IET International Conference-AC and DC Power Transmission (ACDC 2019) and is subject to Institution of Engineering and Technology Copyright. The copy of record is available at IET Digital Library.


