On chain-link based multi-port converters able to connect HVDC and MVDC to AC transmission network

Daniele Falchi[1], Oriol Gomis-Bellmunt[1], Eduardo Prieto-Araujo[1], and Olivier Despouys[2]
[1]CITCEA-UPC, Polytechnic University of Catalonia.
Avinguda Diagonal, 647, 08028 Barcelona, Spain
Email: daniele.falchi@upc.edu, eduardo.prieto-araujo@upc.edu and oriol.gomis@upc.edu
[2]RTE (Réseau de Transport d'Électricité).
La Defense, 7C place du Dôme, Paris, France
Email olivier.despouys@rte-france.com

Keywords

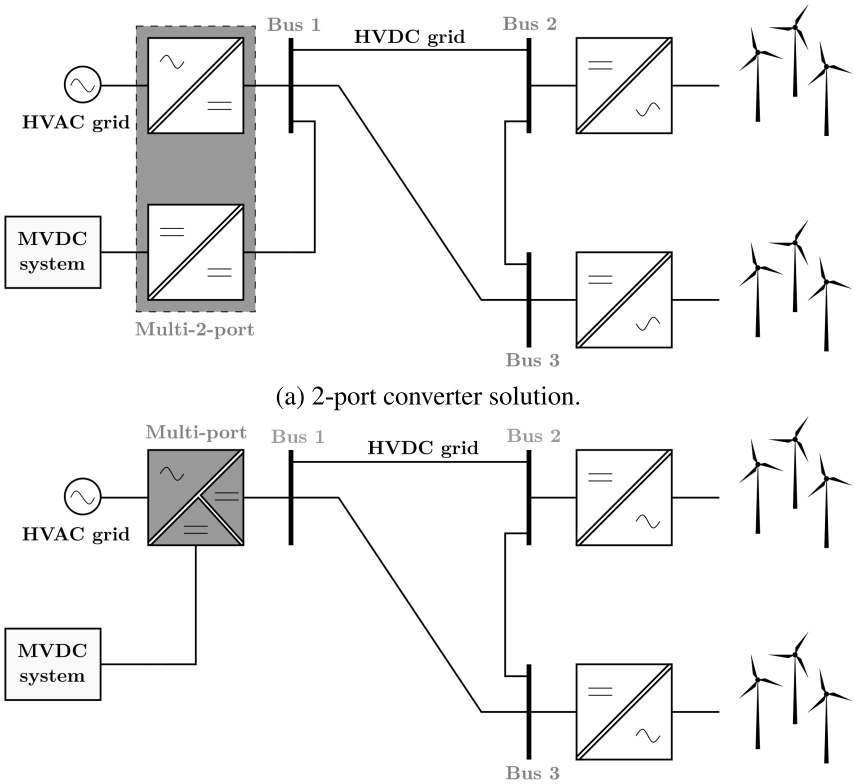
≪Voltage Source Converters (VSCs)≫, ≪High voltage power converters≫, ≪HVDC≫, ≪Converter circuit≫, ≪Multi-port converters HVDC/MVDC/HVAC≫.

Abstract

Multi-port converters may offer an attractive solution to contribute in achieving a more compact, flexible and efficient network. Recently, in literature, a few converter topologies have been proposed to interconnect high-power and high-voltage systems. Most of converter topologies are based on chain-link or modular concept, which is considered a very beneficial way to scale different ranges of voltages and current keeping a high level of reliability, feasibility and power quality. The aim of this paper is to provide, first, a qualitative description of a few selected multi-port converter configurations (non-isolated and fully isolated arrangements) able to interconnect HVDC, MVDC to HVAC systems. And, second, to present a qualitative comparison among cost and footprint of each topology. Also, the paper introduces some practical implications to take into account abnormal conditions e.g fault and port disconnections for such converters.

Introduction

Within the last decade, the power system is facing the increasing amount of renewable and discontinuous energy sources together with the adoption of DC systems integrated in the conventional AC network. Compared to AC technology, DC technology offers improved features, performances, controlling and cost-effectiveness especially looking at long transmission energy systems. In addition to HVDC technology, medium voltage direct current (MVDC) technology has been recently considered for many high power applications and it has been attracting the interest of power distribution and transmission system experts in order to reinforce the grid. MVDC voltages range between 1.5 kV ($\pm$750 V) and 100 kV ($\pm$50 kV) approximately [1], [2]. Offshore renewable, distribution network interconnectors, transmission network interconnectors, rail electrification, shipping and harbors are some applications in which MVDC technology is applied [3] - [6]. Power electronic converters act as key-enablers for modern AC/DC network allowing such a systems integration. Nowadays, MVDC and HVDC energy provision is enabled by conventional AC/DC converters. In the industry, the main VSC reference for HVDC is the Modular Multilevel Converter (MMC) [7]. Regarding MVDC, some converter manufacturers have been proposing various AC/DC topologies, e.g. Two-Level-Converter (TLC) [8], cascade Neutral Point Clamped (NPC) [9] and modular multilevel converter (MMC) [10]. It is also noticed that DC/DC modular converters [11] are under research to provide an interconnection among different DC networks, HVDC and MVDC. However, in order to improve the overall cost, footprint and efficiency of the sub-station, recently, researchers and industries are looking at multi-port converters as another more feasible solution to interconnect HVDC, MVDC to HVAC systems instead of having several two-port converters (AC/DC and DC/DC) linked. Fig. 1 shows a possible application in which multi-port converter technology can be used in a generic system. Table I summarizes some general characteristics depending on the solution, 2-port converter solution and multi-port converter solution.



(a) 2-port converter solution.

(b) Multi-port converter solution.

Fig. 1: 2-port converter vs Multi-port converter solutions.

Table I: 2-port converter solution vs Multi-port converter solutions

	2-port converter based	Multi-port converter based
Cost/Footprint	High	Low
Protection system complexity	Medium	Medium
Load shedding complexity	Medium	High
Fault Ride Through complexity	Medium	High
Power density	Low	High
Energy stored	High	Low

The paper refers to chain-link based converters because of their significant benefits: greater modularity leads to scaling large voltage ranges while maintaining the same semiconductor parameters. Higher fault tolerance, compared with other multilevel converters such as NPCs or FCs (Flying Capacitors) is another key aspect leading to a more reliable solution; in addition chain-link converters achieve a high power quality that contributes to minimize the filtering equipment. The main drawbacks are: first, the complexity of the internal circulating currents, needed for balancing the internal energy stored in sub-module capacitors, second, the inability to perform soft-switching at sub-module level, which might increase overall losses. Anyway, in addition to those strictly related to HVDC, there are several applications in which chain-link based topologies are used: AC/AC as static frequency converter (SFC) [12], DC/AC as motor drive converter [13] and FACTS [14].

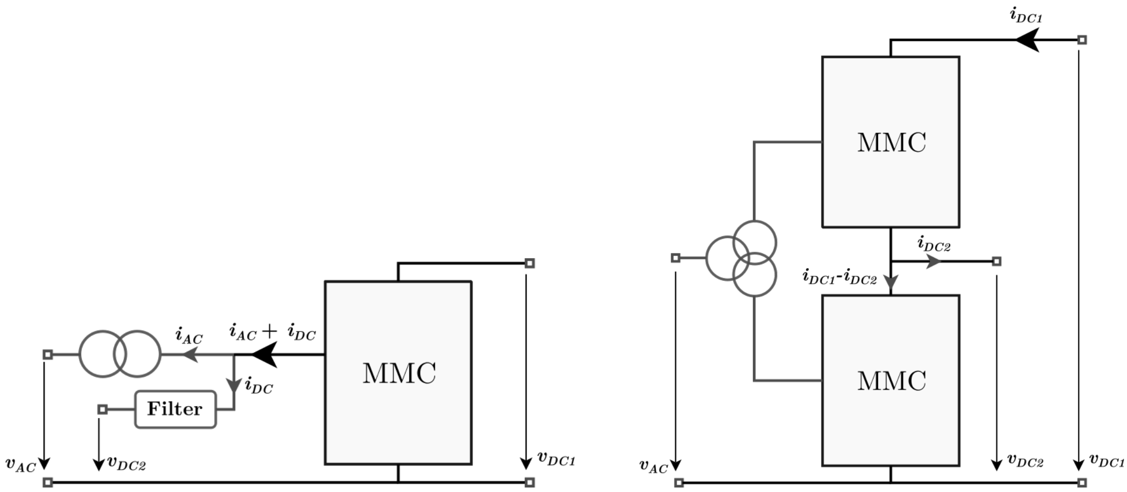
Various multi-port converter proposals have been presented in literature. For most of those, the modelling and control design were developed and tested [15]. However, an initial comparative analysis of different proposed concepts, looking at design implications and operations, might be needed to address the beginning approach to such converters.

Thus, the aim of the paper is to provide a qualitative comparison between four most relevant topologies that can be found in the literature which are based on four different concepts. Hence, two non-isolated and two fully-isolated based topologies were selected, all which are based on two different concepts. The purpose of the proposed work is to introduce the topic with initial insights on different chain-link based multi-port converters interconnecting HVDC, MVDC to HVAC systems. To do so, aspects such as footprint, cost, capabilities and limitation to deal with abnormal conditions (such as fault and port disconnection) were considered.

The following sections include a description among the selected topologies, a qualitative comparison in terms of cost and footprint, a qualitative comparison highlighting main concerns during abnormal conditions and finally, a concluding section.

Non-isolated multi-port topologies

As mentioned above, two non-isolated topologies based on two different concepts have been studied. Both are inspired by existing 2-port converters: the DC/DC Modular Multilevel Converter, M2DC [16], and the DC/DC autotransformer, AT-HVDC [17]. Fig. 2 shows a general representation of the two concepts. For both of them, MMC is the basic block, but each one suggests a different concept to get a multi-port converter. In literature, other similar topologies [18]-[19] based on the same two concepts have been suggested, so that the study focuses on the main two above mentioned references.



(a) M2DC-based concept.

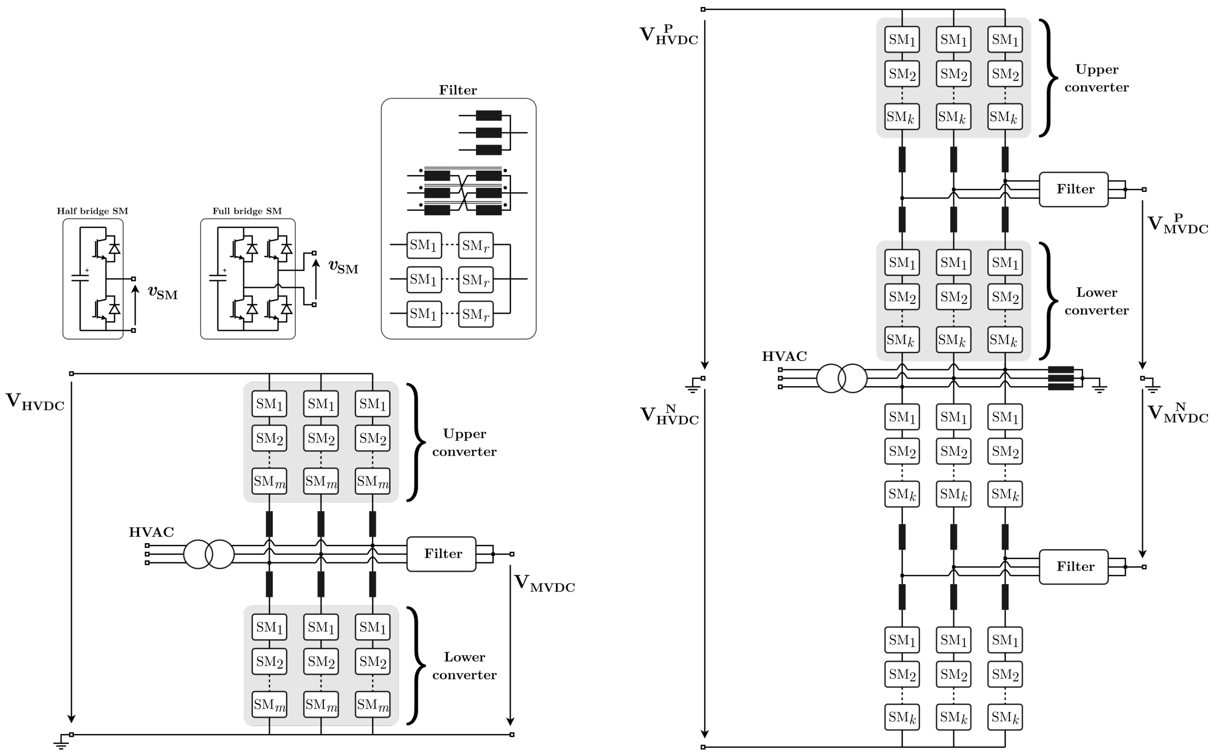
(b) AT-HVDC based concept.

Fig. 2: M2DC and AT-HVDC based concept for non-isolated multi-port converters.

Due to degrees of freedom of MMC at the intermediate point of connection (shunt connection to AC and to MVDC), the M2DC-based converter is able to impose AC and DC components simultaneously. The filter provides a pure DC component to the second DC port. On the other hand, the AT-HVDC converter makes it possible to derive another DC terminal (thanks to series-stacked interconnection of MMCs) to allow a second DC current circulation. The transformer has two main purposes: the first one is to provide energy circulation between upper and lower MMCs in order to achieve the internal energy balancing; the second purpose, by adding a third winding, is to offer a connection to the main AC network.

M2DC based multi-port converter

Asymmetrical and symmetrical monopole arrangements have been proposed in [20] and [21] respectively and Fig. 3 shows both converter arrangements. The first provides a shunt connection of the AC transformer with MVDC filter. The symmetrical monopole version provides the AC transformer connection at the converter midpoint.



(a) Asymmetrical monopole [14]

(b) Symmetrical monopole [15]

Fig. 3: M2DC-based multi-port arrangements.

The configuration depicted in Fig. 3a requires a transformer sustaining DC voltage isolation between ground to neutral. This may have significant impact on the size and weight of this transformer. Internal current circulation between upper and lower converter do not affect the AC current through the AC port, so that AC power can be fully decoupled from internal power circulation. In the configuration depicted in Fig. 3b the transformer does not have to sustain any DC voltage isolation respect to ground but, in such a arrangement, the internal circulating current is not fully decoupled from power to AC terminals, the transformer impedance is in the loop of internal circulation between upper and lower converters, therefore this might lead to an AC-side power limitation or to transformer overrating.

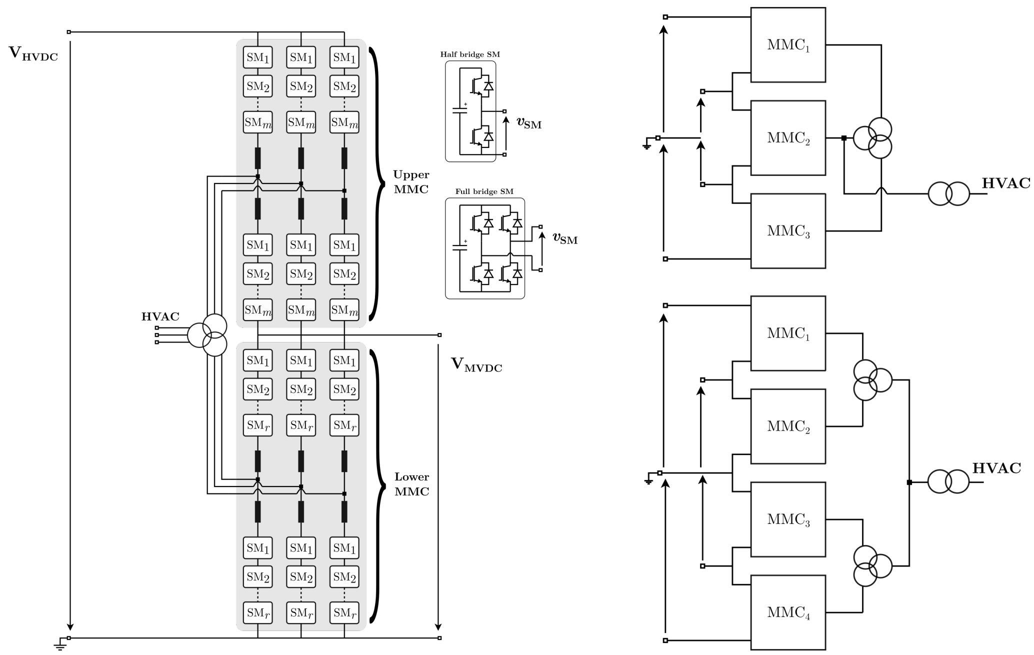
The main purpose of the filter connected in shunt to mid-point of the converter and AC grid is to provide a pure DC component at MVDC terminals preventing any AC components. Depending on the design and functionalities, the type of the filter might be passive (L-C), magnetic (coupled reactors) or active (power electronics based).

In general, a main issue related on this topology concept regards the limited DC voltage step ratio between DC terminals, especially when the DC power step ratios are quite similar. Such limitation is due to the increased value of internal circulating current to provide a balanced operation of the converter and, semiconductor and losses constrains limit the capabilities of such a converter topology. The multi-port operation might help somehow to mitigate such DC voltage step ratio limitation since the rated power of both DC sides is not the same because of the AC-side power contribution.

AT-HVDC based multi-port converter

The AT-HVDC based multi-port converter depicted in Fig. 4 is the most relevant alternative to the M2DC-based converter. Asymmetrical and symmetrical monopole solutions have been proposed in [17] and [22]. In both solutions, due to the series-stacked sub-MMCs construction (upper MMC, lower MMC Fig. 4a), the transformer must sustain a large DC voltage isolation leading to increased size and design complexity.

The AC connection is provided by a multi-winding transformer. It is the same transformer used to



(a) Asymmetrical monopole [10] (b) Sym. monopole and bipole. [11]

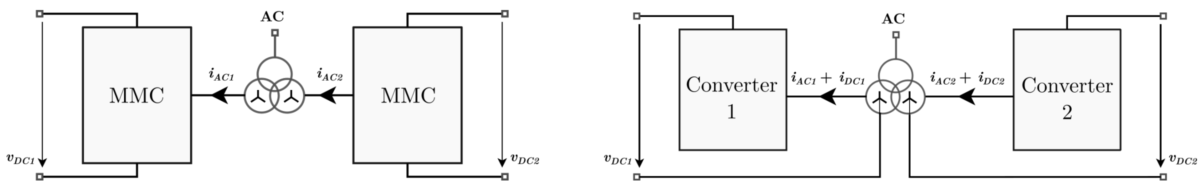
Fig. 4: AT-HVDC-based multi-port arrangements.

transfer power between upper and lower sub-MMCs. Therefore, the transformer must be rated for the nearly full power of the converter and not only rated for the partial power needed for internal energy balancing. Furthermore, in normal conditions, the transformer operates at a fixed frequency (50 Hz or 60 Hz) due to the AC network connection.

Compared to the prior M2DC-based multi-port converter, as a key difference, by acting on the winding turn ratio properly it is possible to minimize the circulating current by maximizing the voltages. Due to this, the stress on semiconductors and losses will be reduced and the converter is able to increase the step ratio capability.

Isolated topologies

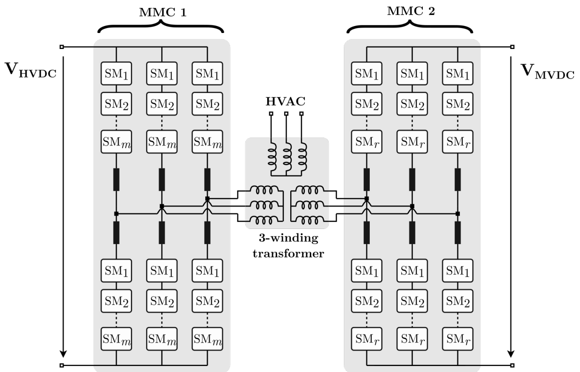
Most of the time, flexible grounding solution at each port and improved safety level might be key requirements to select between multi-port topologies. Fully galvanic isolated multi-port topologies offer such kind of benefits. Nevertheless, compared to non-isolated converters, the cost, size and losses indicators of isolated arrangements will be negatively impacted. Fig. 5 shows the two main concepts used to implement galvanic isolated multi-port converters.



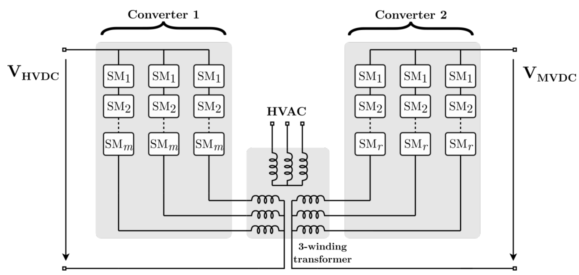
(a) F2F external transformer based concept. (b) F2F internal string transformer concept.

Fig. 5: Galvanic isolated multi-port converter concepts.

The first solution in Fig. 6a is inspired by the most well known front-to-front (F2F) topology [23], which is also based on the DAB (Dual Active Bridge) concept. The transformer is connected in shunt to the AC terminals of MMC converters. The second solution in Fig. 6b is inspired by [24] and provides galvanic isolated ports by installing a series connected transformer to the converter string; still, it is possible to consider the topology based on F2F with incorporated string transformer. In literature, other proposals can be found in which the galvanic isolation is distributed by sub-modules or cells; in this case each cell (or some of them) are equipped by a medium frequency transformer (MFT) [25]. Such a solution is not part of this article, as their main disadvantages is the high voltage isolation requirements for those cell transformers and their low fault tolerance especially considering isolation lost in one sub-module. Hence, for HVDC applications, such a solution might not be adequate. Fig. 6 highlights the two isolated multi-port topologies and the transformer winding connections to the chain-link based converter arrangement.



(a) External transformer multi-port converter.



(b) Series string transformer multi-port converter.

Fig. 6: Fully galvanic isolated multi-port converters.

F2F multi-port converter with external multi-winding transformer

F2F multi-port converter based on external multi-winding transformer is the most relevant reference suggested in literature. With Fig. 6a it is possible to note that two MMC converters share the same AC common coupling by means of the transformer and an additional winding provides the connection of the overall converter to the main AC grid. For such a topology the main advantage is the relatively low design complexity. The transformer has to be rated for the full power ratio of the converter and, in case of asymmetrical monopole at DC terminals, it has to comply to DC voltage isolation respect to the ground. Obviously, the transformer frequency must be equal to the AC grid frequency (50 Hz or 60 Hz). The high power coupling between the transformer windings brings to increase the complexity of the control especially in order to achieve good performances (e.g. AC-Fault Ride Through) during some grid contingencies, such as AC short circuit. Furthermore, since both MMCs are connected to the AC three-phase system, the topology needs full-bridge based sub-modules in both converters to achieve the full blocking capability.

F2F multi-port converter with series string multi-winding transformer

As it is possible to see from Fig. 6b, the main converter purpose is to reduce its overall footprint by incorporating in the transformer its leakage impedance and the impedance of string reactors [26]. The neutral of two wye winding connections provides the DC current circulation to the relative DC port. Then, transformer windings have to be sized to carry AC and DC components and this fact might result in substantial impact on the weight and cost. Furthermore, such a solution provides one degree of freedom less than the conventional MMC; the internal circulating current is not fully decoupled from AC current to the grid, overall performances and internal energy balancing may be limited especially during contingencies such as faults. In general, the transformer saturation due to DC bias has to be considered; although by a proper winding turn ratio and DC current ratio between two converters it is possible to ensure a zero net DC flux within the core in normal operation, this is not true when one of the two DC port is not demanding power, in the last case transformer core needs to be sized in order to prevent the saturation. To deal with the DC bias, it is possible to install different transformer topologies able to eliminate the DC bias within the core properly, for instance, one of these method is to use a zig-zag transformer [27].

General comparison between multi-port topologies

Multi-port converter solutions, compared to multi-2-port converter ones, offer relevant advantages in reducing the footprint, saving cost and materials. This is true for the multi-module non-isolated and isolated solutions. Table II summarizes some general characteristic that isolated arrangements offer with respect to non-isolated topologies in a generic system. As above mentioned, full galvanic isolated converters offer a more secure and flexible solution to interconnect HVDC, MVDC to HVAC, and most of the time these are required by the application. Anyway, such benefits lead to have higher costs and larger footprint compared with non-isolated converters.

Table II: General pros and cons on having a galvanically isolated converter.

Pros	Cons
High flexibility on grounding	Increased number of switches
High flexibility on DC voltage step ratio	Impact on the footprint
Improved security operating condition	Increased losses
Increased buck-boost capability	DC bias (saturated area)*

*For the transformer.

Since the galvanic isolation is a requirement from the application, the following sections provide a qualitative comparison between non-isolated topologies and isolated topologies separately.

Footprint and cost

Tables III and IV summarize the number of main components present in the selected topologies, non-isolated and isolated converters respectively. The comparison focuses on the number of sub-modules, reactors, transformers and filters. V_{SM} is the rated voltage of each sub-module, V_{HVdc} and V_{MVdc} the voltages at the DC terminals and n_{leg} the number of the converter phases. Special transformer or conventional transformer depends on the topology, special transformer has to be sized to sustain a large DC voltage isolation respect the ground (AT-HVDC based case) or in case to allow AC and DC current circulation (F2F series winding transformer based).

Table III: Non-isolated multi-port converters.

	SMs	String reactors	Transformer	Filter
M2DC based	$2n_{leg}V_{HVdc}/V_{SM}$	$2n_{leg}$	✓Conventional	✓
AT-HVDC based	$2n_{leg}V_{HVdc}/V_{SM}$	$4n_{leg}$	✓Special	-

Table IV: Isolated multi-port converters.

	SMs	String reactors	Transformer	Filters
F2F shunt based	$2n_{leg}(V_{HVdc}+V_{MVdc})/V_{SM}$	$4n_{leg}$	✓Conventional	-
F2F series based	$2n_{leg}(V_{HVdc}+V_{MVdc})/V_{SM}$	-	✓Special	-

In terms of footprint and cost the two non-isolated solutions might be quite equivalent; M2DC-based converter use a conventional transformer to connect to AC grid but a filter sized for the full AC voltage is needed. AT-HVDC based converter does not need a filter but a special three-winding transformer sustaining a large DC voltage isolation to ground is required. For isolated converters, although the F2F shunt based converter requires more string reactors than F2F series based converter, the complexity and footprint of transformer should be considerably less impacting on cost and footprint.

Fault and protection implications

The objective of this section is to give an initial evaluation on the main implications to consider depending on the topology in anomalous conditions such as fault. Fig. 7 shows three cases of fault selected for this analysis: C1 represents a symmetrical short circuit fault at AC port. C2 represents a pole to ground short circuit fault at HVDC port. C3 represents a pole to ground short circuit fault at MVDC port. Table V summarizes such observations for the four selected topologies.

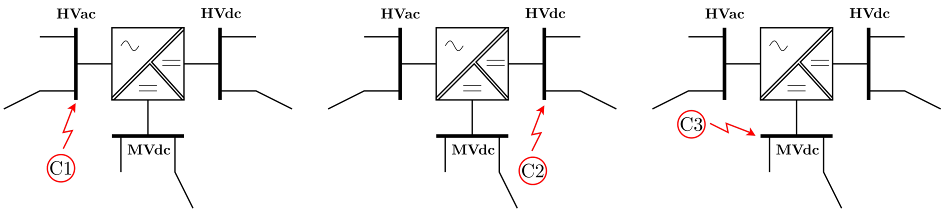


Fig. 7: Case of fault on multi-port converter.

Table V: Topologies implications in different fault conditions.

(a) M2DC-based converter.

	M2DC-based
C1	Converter is able to perform the FRT and DC/DC operation is still possible.
C2	Fault block: FB SMs to limit the short circuit current from AC and MVDC port.
C3	Fault block to HVDC: proper number of SM at the upper side converter.
	Fault block to HVAC: proper number of FB SMs at the lower side converter.

(b) AT-HVDC-based converter.

	AT-HVDC-based
C1	Converter is able to perform FRT. DC/DC operation limited by current.
C2	Fault block: FB SMs to limit the short circuit current from AC and MVDC port.
C3	Fault block to HVDC: proper number of SM at the upper MMC converter.
	Fault block to HVAC: proper number of FB SMs at the lower MMC converter.

(c) F2F shunt transformer based.

	Shunt multi-winding transformer based
C1	Converter is able to perform FRT to AC. DC/DC operation limited by current.
C2	Fault block to HVdc: FB SMs to HVdc side MMC to limit the short circuit current.
C3	Fault block to MVdc: FB SMs to MVdc side MMC to limit the short circuit current.

(d) F2F series string transformer based.

	Series multi-winding transformer based
C1	Converter is able to perform FRT to AC. DC/DC operation limited by current.
C2	Fault block to HVdc: FB SMs to HVdc side MMC to limit the short circuit current.
C3	Fault block to MVdc: FB SMs to MVdc side MMC to limit the short circuit current.

Port disconnection - load change implications

Each converter port of the converter is rated at a specific power. Here the assumption is that, in case of load change or port disconnection at the port, the overall converter has to continue to operate adjusting the power flow according with the new sets (P^*_{dc-dc} and P^*_{ac-dc}) of references between the remaining ports. Fig. 8 shows three cases of port disconnections (load/source): C1 represents the HVAC terminals disconnection, C2 represents the HVDC terminals disconnection and C3 represents the MVDC terminals disconnection.

For M2DC based topology, referring to table VIa, the worst case occurs when HVDC terminals are disconnected; high internal upper-lower energy unbalancing could occur leading high current stress in order to achieve the balancing among upper-lower side.
For AT-HVDC based topology, referring to table VIb, when AC is disconnected a DC/DC mode operation is possible and the transformer provides the energy transferring between upper MMC and lower MMC in order to achieve internal balancing. When the HVDC is disconnected the upper MMC should not provide any active power to the AC terminals and the lower MMC works to achieve the AC/DC power

conversion. When the MVDC is disconnected the converter works similarly to a bipolar MMC, and the AC power is distributed between upper and lower MMC.
Referring to table VIc, F2F based on shunt connected transformer, the worst case occurs when AC port is disconnected; two MMCs have to change the mode of operation, keeping one them controlling the AC voltages and the other controlling the power. Finally, from table table VId, F2F based on series string connected transformer, the worst case occurs when one of two DC terminals is disconnected; DC flux cannot be compensated leading the transformer to work in saturated area, unless a special transformer is used (zig-zag transformer for instance).

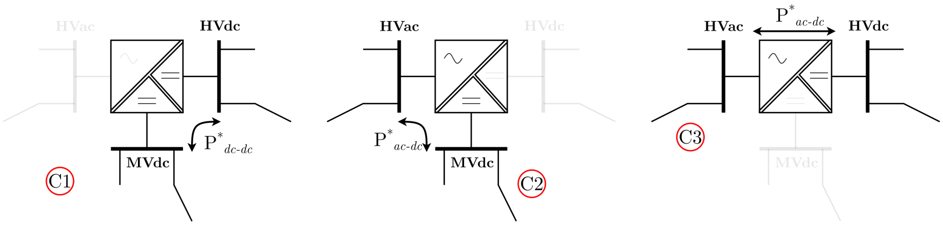


Fig. 8: Different load shedding cases in multi-port converter.

Table VI: Topologies implications in different port disconnection events.

(a) M2DC-based converter.

	M2DC based converter
C1	Pure DC/DC operation with considering a new P^*_{dc-dc}.
C2	Pure AC/DC operation with considering a new P^*_{ac-dc}. High upper-lower energy unbalancing.
C3	Pure AC/DC operation with considering a new P^*_{ac-dc}.

(b) AT-HVDC-based converter.

	AT-HVDC based converter
C1	Pure DC/DC operation with considering a new P^*_{dc-dc}.
C2	Pure AC/DC operation with considering a new P^*_{ac-dc}. Upper converter exchange zero active power.
C3	Pure AC/DC operation with considering a new P^*_{ac-dc}. AC/DC as a bipolar MMC

(c) F2F shunt transformer based.

	Shunt multi-winding transformer based converter
C1	Pure DC/DC operation with considering a new P^*_{dc-dc}. One converter form the grid the other controls the power.
C2	Pure AC/DC operation with considering a new P^*_{ac-dc}. HVdc side converter can provide just reactive power.
C3	Pure AC/DC operation with considering a new P^*_{ac-dc}. MVdc side converter can provide just reactive power.

(d) F2F series string transformer based.

	Series multi-winding transformer based converter
C1	Pure DC/DC operation with considering a new P^*_{dc-dc}. One converter form the grid the other controls the power.
C2	Pure AC/DC operation with considering a new P^*_{ac-dc}. DC biased transformer.
C3	Pure AC/DC operation with considering a new P^*_{ac-dc}. DC biased transformer.

Conclusion

After presenting the main four topologies based on chain-link concept, the paper provides a qualitative analysis of each of them highlighting the main implications in design, footprint and during anomalous grid contingencies depending on the four different concepts. M2DC based topology and AT-HVDC topology are very similar in footprint and cost, regarding performances in abnormal conditions, while M2DC based converter might offer a better response during AC FRT condition than AT-HVDC based converters. Regarding isolated topologies, F2F based on series string connected multi-winding transformer might offer a reduced footprint compared to F2F based on shunt connected multi-winding transformer, but it results in more limitations and complexities in sizing and control, especially during grid contingencies.

References

[1] CIGRE WG C6.31: Medium Voltage Direct Current (MVDC) Grid Feasibility Study

[2] Rentschler, A and Kuhn, G and Delzenne, M and Kuhn, O.: Medium voltage dc, challenges related to the building of long overhead lines, PES Transmission and Distribution Conference and Exposition (T&D). IEEE. 2018

[3] Hay S. et al.: MVDC Technology Study-Market Opportunities and Economic Impact, Scottish Enterprise, Report 9639-01 (2015), R0

[4] Dujic D.: Medium Voltage Direct Current-Technologies and Systems, KEYNOTE at Ee2017-19th International Symposium on Power Electronics. POST TALK. 2017.

[5] Stieneker M. and W De Doncker R.: Medium-voltage DC distribution grids in urban areas, 2016 IEEE 7th international symposium on power electronics for distributed generation systems (PEDG). 2016, pp. 1-7.

[6] Verdicchio A. et al.: New medium-voltage DC railway electrification system, IEEE Transactions on Transportation Electrification 4.2 (2018), pp. 591-604.

[7] R Marquardt.: A new modular voltage source inverter topology. Conf. Rec. EPE 2003.

[8] Skytt A.K., Holmberg P. and Juhlin L.E.: HVDC Light for connection of wind farms, (2001).

[9] Tibin J. et al.: Analysis of harmonic transfer through an MVDC Link, (2019).

[10] AG Siemens. MVDC PLUS: Medium Voltage Direct Current Managing the future grid. Whitepaper (2017).

[11] Kung S. H. and Kish G.J.: A Modular Multilevel HVDC Buck–Boost Converter Derived From Its Switched-Mode Counterpart, IEEE Transaction On Power Delivery, (2018).

[12] Bessegato L. et al.: Control and Admittance Modeling of an AC/AC Modular Multilevel Converter for Railway Supplies, IEEE Transaction On Power Electronics, (2019).

[13] Siemens: Principles of Modular Multilevel Converter Topology, Whitepaper, (2019).

[14] Fang Zheng Peng et al.: A Multilevel Voltage-Source Inverter with Separate DC Sources for Static Var Generation, IEEE Industry Applications Conference Thirtieth IAS Annual Meeting, (1995).

[15] Rouhani M.and Kish G.J.: Multiport DC–DC–AC Modular Multilevel Converters For Hybrid AC/DC Power Systems, IEEE Transaction On Power Delivery, (2020).

[16] Norrga S.: Bidirectional unisolated dc-dc converter based on cascaded cells. US Patent 9,484,808. DCDC Nov. 2016.

[17] Bakran M., Knaak H. and Schon A.: Modular multilevel DC/DC converter for HVDC applications. WO Patent 2014/056540 A1. Apr. 2014.

[18] Lin W., Wen J. and Cheng S.: Multiport DC–DC Autotransformer for Interconnecting Multiple High-Voltage DC Systems at Low Cost, IEEE Transaction On Power Delivery, (2015).

[19] Li Y. Liu D. and Kish G.J.: Generalized DC-DC-AC MMC Structure for MVDC and HVDC Applications, 20th Workshop on Control and Modeling for Power Electronics (COMPEL), (2019).

[20] Bakran M. and Schon A.: DC to DC Converter. WO Patent 2016/138949 A1. Sept. 2016.

[21] Papastergiou K. and Stamatiou G.: AC/DC multicell power converter for dual terminal HVDC connection. US Patent 9,065,328. June 2015.

[22] Schon A. and Bakran M.: High power HVDC-DC converters for the interconnection of HVDC lines with different line topologies, 2014 International Power Electronics Conference (IPEC-Hiroshima 2014-ECCE ASIA). IEEE. 2014, pp. 3255-3262.

[23] Kenzelmann S. et al: Isolated DC/DC Structure Based on Modular Multilevel Converter, IEEE Transaction On Power Electronics, (2015).

[24] Oates C.: A methodology for developing 'Chainlink' converters, 13th European Conference on Power Electronics and Applications, (2009).

[25] Ferreira Costa Levy et al: Comparative Analysis of Multiple Active Bridge Converters Configurations in Modular Smart Transformer, IEEE Transaction On Industrial Electronics, Vol. 66, No. 1,(2019).

[26] Tenca P. et al.: Patent: High voltage DC/DC converter with transformer driven by modular multilevel converters (MMC), WO 2013/075735 (2013).

[27] Serbia N. et al.: Half Wave Bridge AC/DC Converters – From diode rectifiers to PWM multilevel converters, PCIM Europe (2014).