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State of the Art DC-DC Converter Topologies for the Multi-Terminal DC Grid Applications: A Review

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***Abstract*—The high power dc-dc converters emerged as the key circuit element for the future multi-terminal dc grid due to rapid increase in the number of HVDC transmission lines. Beside power conversion, it can provide many functionalities such as bidirectional power flow, power flow control and dc fault isolation. Recently, many high power dc-dc converter topologies have been proposed in the literature for applications in the dc grid. The problem with these, however, is that they are not classified in to various categories based on different parameters such as internal isolation, power density or conversion ratio. This review proposes a taxonomy of most efficient state-of-the-art dc-dc converter topologies based on the structural affinities. Most prominent converters are classified in to two major groups based on the internal isolation. Then, the basic structure, operating principle and performance capabilities accompanied by key advantages and major limitations of each converter is discussed. Furthermore, this study highlights the most suitable converter topologies for the application of HVDC grid interconnection.**

Keywords—HVDC transmission, high power dc-dc converters, modular multilevel converters

I. Introduction

The rapid increase of energy demand and rising environmental concerns have driven the researchers to explore the coupling of renewable energy sources to the power system [1]. For such applications, the Voltage Source Converter (VSC) based HVDC transmission has been considered as the most optimal solution for interconnecting the large offshore windfarms to the traditional power system. Recently, there is great increase in the number of Point-to-Point (P2P) HVDC transmission lines that creates the idea of forming a multi-terminal dc grid [2]–[4].

As compared to the traditional P2P connection, such design consists of more than one inter-connection path between two converter terminals. This structure ensure better result in terms of high efficiency, increased redundancy and secure power flow control. However, it faces many technical challenges in the practical realization due to the inclusion of the existing non-standardized P2P HVDC links [2], [3]. These HVDC links differ in voltage levels, grounding schemes and dynamic responses due to manufacturing at different times by different manufacturers. In such case, there is a need of an interface element such as a dc-dc converter for the practical realization of dc grid [5], [6]. Table I represents the voltage, power and transformation ratio characteristics for HVDC applications and Table II shows the key requirements of dc-dc converters for HVDC grid interconnections [7].

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The high power dc-dc converters dedicated for dc grids can behave similar to that of ac transformer used in the traditional ac system. However, it can also provide other functionalities such as power flow control, grid voltage regulation, dc fault isolation and the interconnection between two dc systems of different grounding schemes such as monoplor vs bipolar [8]–[12].

Although, many dc-dc converter topologies have been proposed in near past for applications in the dc grid. However, at an early stage, it is more beneficial to investigate the different groups of the converters based on the similar design and the operating principle rather than the individual study of each topology in detail. The extant literature lacks such classification and only a few papers summarize such , they do not explain the transformer-less designs in detail and all the mentioned references were from 2014 or earlier [12].

This paper reviews the most recent and state-of-the-art literature to figure out the most efficient and emerging topologies of dc-dc converters for employment in the dc grid. Accordingly, this research work classifies the proposed converters into two main categories that are the isolated and the non-isolated converters. Fig. 1 shows the proposed categorization of the dc-dc converters. The classification is based on the isolation transformer interfaced between the two dc sides. Each converter topology has been discussed in detail along with its operating principle, the basic schematic diagram and the key technical features. In addition, their performance capabilities together with their advantages and disadvantages are also provided. Thus, this review study can be used as a selection guide by the researchers who want to contribute to this area. The rest of the paper is organized as follows: Section 2 presents the isolated topologies and the non-isolated circuits are discussed in Section 3. Section 4 presents the discussion and finally, the paper concludes in Section 5.

II. Isoltaed Topologies

Most circuits that fall into the category of isolated topologies depict the Dual Active Bridge (DAB) structure. Such design consists of two ac-dc converters that are linked through internal ac transformer. This design have the capability of galvanic isolation that is very important for the high transformation ratio applications. It is also very helpful in the interconnection of HVDC links of different grounding schemes. The isolated topologies are further classified into three different structures such as Two-Level DAB, Modular-Multilevel DAB, and the Multi-Module Cascaded DAB.

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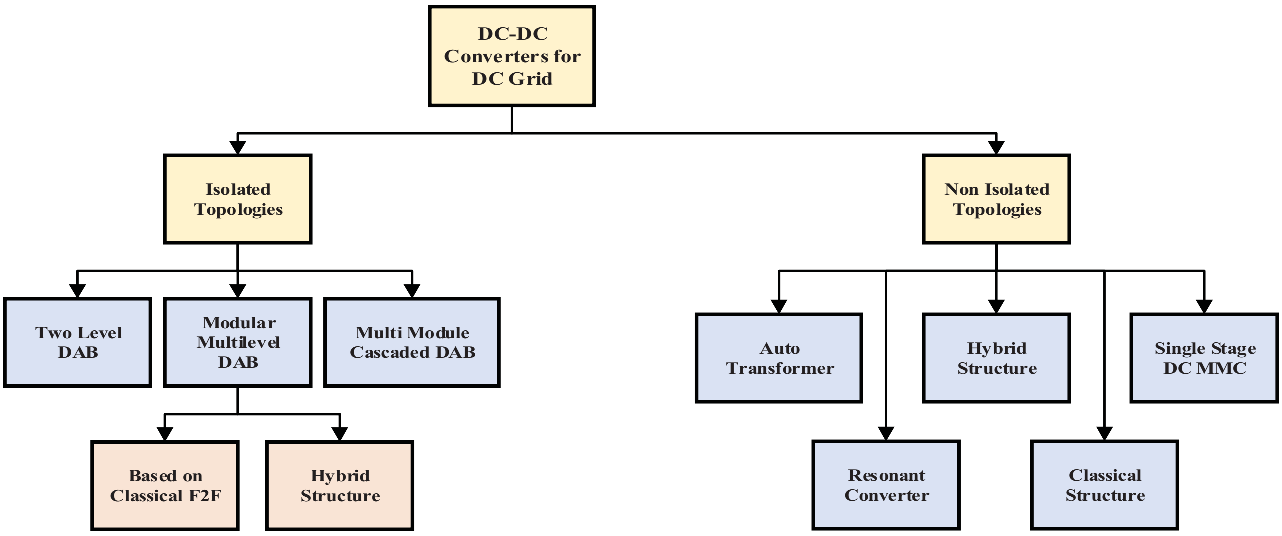


Fig. 1. Proposed classification of converters based on internal isolation

TABLE I. VOLTAGE, POWER & TRANSFORMATION RATIO FOR DIFFERENT APPLICATIONS IN HVDC TRANSMISSION

Parameter	Classification	Range
DC voltage rating at HV side	• Medium • High	• Vdc < 100kV • Vdc ≥ 100kV
Amount of power to be transferred	• Low • Medium • High	• Pdc < 50MW • 50MW ≤ Pdc < 500MW • Pdc ≥ 500MW
Ratio of Transformation	• Low • Medium • High	• 1 < R ≤ 1.5 • 1.5 < R ≤ 5 • R ≥ 5

TABLE II. KEY REQUIREMENTS OF DC-DC COVERTERS FOR HVDC GRID INTERCONNECTION

Parameter	Range
Step Ratio	Low
Power Capacity	High
Galvanic Isolation	No
Weight/Footprint	Not critical
Bi-directionality	Yes
HVDC Converter scheme	Both Monopolar and Bipolar in the same converter
Availability/Reliability	Extremely Important
DC fault blocking capability	Yes
Target cost	Not critical

A. Two Level DAB Converter

The basic structure of the two-level DAB converter is presented in Fig. 2. In this configuration, two VSC bridges are interconnected through an intermediate transformer commonly known as Front-to-Front (F2F) connection [13]. Such design utilizes the series connected Insulated Gate Bipolar Transistors (IGBTs) to enable operation at high dc voltages. Typical fundamental frequency in the internal ac-link lies in the range of 250 Hz to 1 kHz that reduces the weight and size of the converter elements. The load angle between two converters acts as a control variable to maintain the power flow between the two dc sides [14].

Although, it has simple structure and straight forward operating principle, it offers many drawbacks for utilization in shigh voltage applications. In case of high dc-voltages, it imposes high dv/dt on the internal medium frequency transformer which is intolerable for the proper operation of the transformer that causes insulation and electromagnetic interference issues. Beside this it also requires complex strategies for the dynamic and static voltage balancing on the transistor valves.

B. Modular Multilevel DAB

This design consists of two Modular Multilevel Converters (MMC) that are coupled through an internal intermediate transformer [15] as shown in Fig. 3. In order to control the power flow, both the MMCs are controlled in such a way that they produces phase shifted ac output at the terminal of the transformer. The ac voltage can be generated by the insertion of the required number of Submodules (SM) in the respective arm of the converter phase leg [16], [17]. It can utilize different types of SMs such as Half Bridge (HB) and Full Bridge (FB) SMs. The HB SM provides only unipolar voltage while the FB offers bipolar voltage that can be utilized in case of dc fault blocking [18].

There are two different modulation schemes to operate the internal ac-link of the converter, known as the multilevel modulation and the quasi (trapezoidal) two-level modulation [19]. These can be utilized to for more reliable operation and reduced footprint of the converter. For example, the trapezoidal modulation inherently reduces the size of switches, transformer and other passive elements under operation at high frequency. However, the internal ac transformer design at such high frequencies is a challenging task [20]. On the other hand, the multilevel sinusoidal modulation offers low switching losses and less voltages stress as the cost of low power density. Therefore, it always require a tradeoff between the switching losses and overall footprint.

As the MMC-DAB require two full rated dc-ac converters, therefore its size and cost is higher as compared to others. To tackle this issue, some hybrid versions of the MMC-DAB are proposed in the recent research works [21]–[23] . Fig. 4 shows the structure of one of the hybrid version that is known as Transition Arm Converter (TAC) [21]. In such design, some the SMs in the lower arm of the converter are replaced by the transistor valves. This combination offers the advantages of both the two-level VSC and the MMC. As the basic structure MMC-DAB changes, so each hybrid design uses its own control methods.

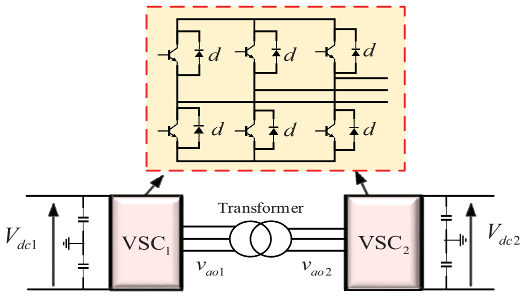


Fig. 2. VSC based two-level DAB

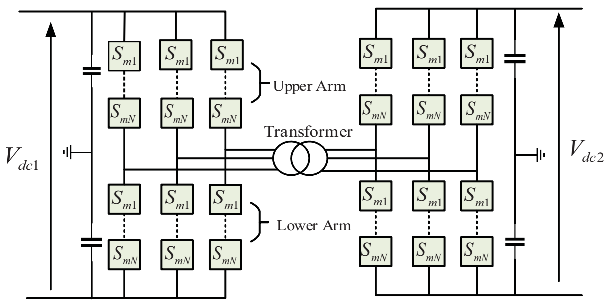


Fig. 3. Classical MMC based DAB converter

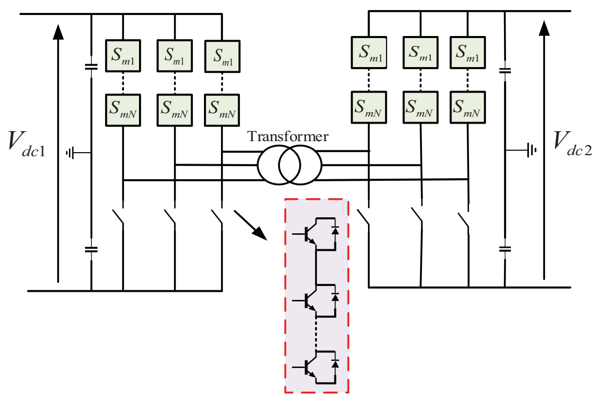


Fig. 4. Hybrid structure of calssical MMC-DAB

C. *Multi-Module Cascaded DAB*

Fig. 5 shows the basic structures of the multi-module cascaded DAB dc-dc converters. This high voltage structure can be actualized by interconnecting the multiple low voltage and low power modules with their inputs and outputs connected in series or parallel [24]. This design alleviates the need for the series connected transistors which in turns reduces the design complexity. In this topology, each cell only handles a limited amount of the total power that is useful in the reduction of the current rating of the semiconductors [25].

In this multi-module structure, the cells can be interconnected in either series or parallel for high voltage or high current applications. When modules are connected in the parallel, it distributes the main current in each of the elementary cell. On the other hand, the series connection results in the distribution of voltage in each cell. However, these two different schemes can be combined in different manners for the specific HVDC applications [26], [27]. The multi-module converter requires individual control of each elementary converter in the classic DAB way.

The multi-module DAB converter has many advantages such as the modular and the scalable structure. Besides this, it allows the interconnection of inputs and outputs in multiple ways to provide high stepping ratios. However, such topology uses multiple transformers interconnected between two individual converters. Thus, it requires very high insulation that restricts its application to the medium voltage conversion.

III. Non-Isolated Topolgies

As compared to the isolated dc-dc converter topologies, there are more non-isolated topologies that are recently proposed for the applications in the high voltage dc grid. These converters don't use the internal medium transformer between the two dc sides. The non-isolated converter topologies are sub-categorized in five different structures, which are DC Autotransformer, Resonant Converter, Hybrid Structure, Classical Structure and Single-Stage DC-MMC.

A. *DC Autotransfromer*

Fig. 6 shows the basic structure of the Autotransformer based dc-dc converter. In comparison to the well-established F2F-MMC, this converter utilizes two high voltage dc-ac structures that are connected in series at the dc ports and their ac sides are coupled through an interconnected ac transformer [28], [29]. It is possible to actualize this structure with the existing HVDC converters technologies such as the two-level or three-level VSC and MMC [30].

This design differs from the classical F2F configurations in operation where all the power transfers from one dc side to another through the internal ac link. Here in, only a specific a specific amount of power transfer through the ac link while the remaining amount of power transfers directly to the low-voltage converter through the common mode (dc current) component of the upper arm current. This feature is quite advantageous and it successfully reduces power losses and the rating of the cross-connected ac transformer. Beside this, it also decreases the size of the individual converter due to series connection. However, this design loses such qualities at high transformation ratios. Hence, this design will be more suitable for such applications that require medium or low conversion ratios.

B. *Resonant Converter*

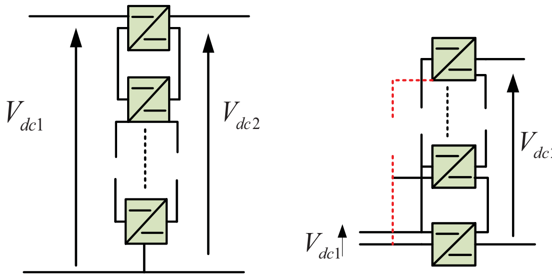
The operation of the resonant converter depends on the transfer of power from one side to another with the help of the inductor-capacitor (LC) tank. Such converter topology uses the phenomenon of resonance as a step-up mechanism for the transformer operation. Beside this, it also achieve the Soft Switching (CS) of the semiconductors [31], [32]. They can be further classified in the single stage and multi-stage based on the number of LC tanks used inside.

In single stage [33]–[35], the dc-dc conversion is achieved by utilizing the concept of dc-ac-dc conversion without internal isolation as used in the F2F configurations. In such design, the VSC bridges that are implemented with the series connection of semiconductor switches are interconnected on their ac side through internal LC tank as shown in Fig. 7. In [32], an internal LCL T-network was used for resonant element . On the other hand, this design proposed the concept of parallel LC tank along with a voltage doubler circuit for the resonant element [36].

On the other hand, the multiple stage resonant dc-dc converter utilizes multiple low power LC tanks for the resonance mechanism [37], [38]. As compared to the single stage, this design is modular in nature and has less complexity.

In such case, the LC tanks are activated in the sequential manner and the power transfers from tank to another until it is reaches to the high voltage terminal. For step-down operation, similar process is repeated in an inverse manner.

Although, the single-stage and multiple-stage resonant converter topologies are designed for high conversion ratios. However, both of these design has major drawbacks. In single stage, the passive components such as capacitors are exposed to high voltage stress due to high dc voltages. Beside this, the current and voltage ratings of the resonant elements should be very high as all power transfers through elements from one side to another. On the other hand, the multiple-stage offers resonant converter offers less voltage stress on the resonant elements. However, this design suffers from the unequal distribution of currents and voltages that makes it unsuitable for modular structure in case of high voltage applications.



(a) (b)

Fig. 5. Multi-Module cascaded DAB conveter

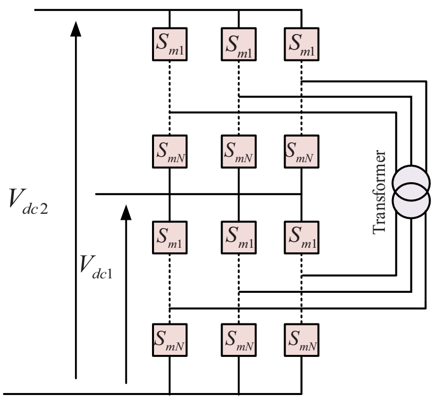


Fig. 6. Autotransformer based dc-dc converter

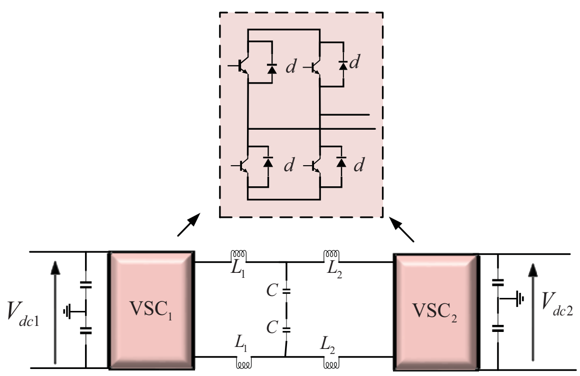


Fig. 7. Resonant dc-dc converter

C. Hybrid Structure

In [39], the authors has proposed a multiphase transformer less dc-dc converter for high voltage applications. It consists of several semiconductor switches and cascaded SMs. In general, a series switch can be realized as a two-level converter that acts in controlled manner to link the SM string with the high voltage and low voltage sides of the converter for the energy exchange. On the other hand, the cascaded SMs, of this hybrid structure acts as the energy storing element. The basic structure of the hybrid transformer less dc-dc converter is shown in Fig. 8. The dc poles are connected in series with the two-level converters (switches) and a chain link of the series connected SMs is grounded. The inductor (L) provides the connection of phase leg with the negative dc pole of the converter.

In the hybrid structure, the HB-SMs in the phase leg should be rated for high voltage, enabling in this way the efficient switching between V_{dc1} and V_{dc2}. Although, such design does not exposes the cell capacitors to high voltage stress, however, it cannot handle dc fault on high voltage (V_{dc2}) side of the converter. Furthermore, it exposes the diodes of the high voltage side switches to a high current stress. In order to block the dc fault current propagation, the hybrid structure is enhanced by employing the FB-SMs. Although, this approach achieves good dc fault blocking, however, usage of more switches in the conduction path increases the power losses.

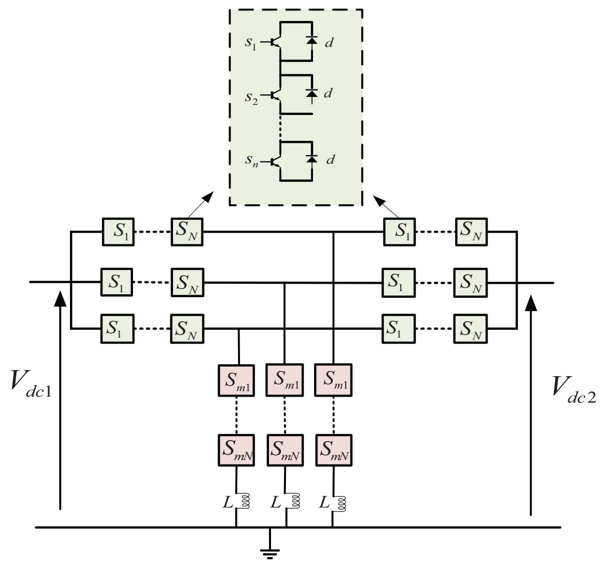


Fig. 8. MMC based hybrid dc-dc converter

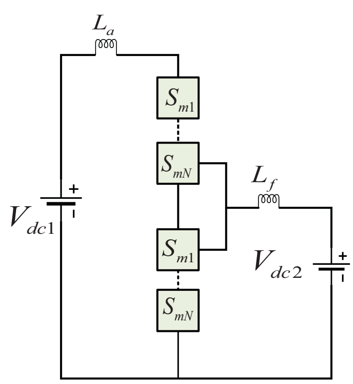


Fig. 9. MMC based classical buck conveter

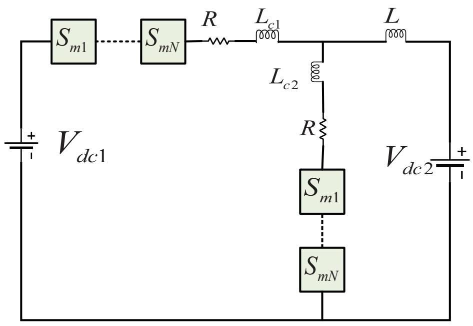


Fig. 10. MMC based classical buck-boost converter

D. Classical Structure

In recent research articles, several families of non-isolated dc-dc converters based on the classical buck, boost and buck/boost were proposed [40], [41]. The normal switches in classical converters have been replaced by the HB SM-strings that are derived from the classical MMC [18], [42]. The HB SMs serve for the voltage clamping and offer better control features. The SMs also produce step transitions to control the change of voltage (dv/dt) across the inductor. In [41], the operation of the converter was verified in the buck/boost mode, while only [40] provides the buck operation. Fig. 9 and Fig. 10 represents the classical buck and buck/boost converters design, respectively.

Although, the classical structure based dc-dc converters are modular in structure with high transformation ratio at low power levels, they fall behind because of the high-energy requirement for the energy-storing element (an inductor) in case of buck/boost operation. Besides this, both the aforementioned works do not consider its dc fault handling capability that is very important for a reliable operation of the MTDC grid.

E. Single-Stage DC-MMC

The basic design of a transformer-less single-stage MMC based dc-dc converter is shown in Fig. 11. As compared to the MMC-DAB, such design performs single stage dc-dc conversion without the employment of internal medium frequency transformer [9], [11], [43]. It uses multiple interleaved strings of the cascaded SMs for the bidirectional operation [44]. Two loops known as the primary (ac) and the secondary (dc) power loops are used for the capacitor voltage balancing and power transfer between two dc sides. This design utilizes the concept of circulation of internal ac current in the arms of the phase legs to achieve capacitor voltage balancing and single-stage dc-dc conversion [45]. The circulating currents are established by the reactive elements (L_r) that are linked with each string of SMs [46]. This converter always require the passive filters such as inductors to prevent the ac current components from entering in to the dc buses [45]. However, different control strategies can also be used to handle this case [9], [47].

Such converter operates in hard-switching mode, it uses MMC SMs that operates at low switching frequency, hence conduction losses of the semiconductors covers the overall losses. Although, increasing the switching frequency of the internal ac current can reduce the size of the passive elements, it increases the power losses and offers low efficiency. Even though the frequency and the magnitude of the circulating ac current can be chosen randomly, it should be selected as minimum as possible to maximize the efficiency.

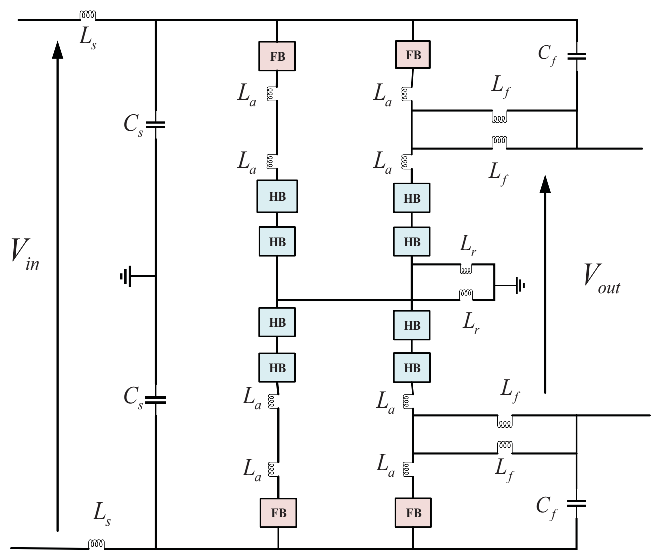


Fig. 11. Basisc structure of the single stage DC-MMC

This structure offer better results in terms of modular and scalable structure, high reliability, low losses and better switch utilization. However, it results in internal reactive power circulation and high electrical stress on the SM switches due to the presence of internal ac current. Beside this, they always require high filtering that limit its application medium transformation ratios.

IV. Discussion

The dc-dc converter is the most significant equipment for the practical realization of the MTDC gird. It can perform various functions such as the dc voltage matching, bidirectional power flow and dc fault blocking. This paper highlights the role and the operation of the various converter topologies for the dc-dc conversion at high voltage levels.

Each topology is thoroughly analyzed and discussed in detail. The selection of the proper converter topology for the specific application and operating conditions is not an easy task. It depends on various important parameters such as the conversion ratio, voltage ratings, power density and the isolation between the converters. Table III presents the power density and conversion ratio of the different converter topologies Furthermore, Table IV shows the key features and major limitations of the various converter topologies.

TABLE III. Power Density and Conversion Ratio of the Different Converter Topologies

Type of Converter	Power Density	Conversion Ratio
Two-Level DAB	Low	Low
MMC-DAB	High	Low
Multi-Module Cascaded DAB	High	High
Autotransformer	High	Medium
Resonant Converter	High	High
Hybrid Structure	High	Medium
Classical Structure	Low	High
DC-MMC	High	Medium

TABLE IV. KEY FEATURES AND MAJOR LIMITATIONS OF DIFFERENT CONVERTER TOPOLOGIES

Type of Converter	Key Features	Major Limitations
Two-Level DAB	• Simple structure • Easy operation	• Requires voltage balancing strategies • Imposes high voltage stress on the internal transformer
MMC-DAB	• Modular and scalable structure • Offers high efficiency	• Require two full stage dc-ac conversion stages
Multi-Module Cascaded DAB	• Modular and scalable structure • High efficiency • Less complex design	• Requires very high insulation due to high number of individual transformers
Autotransformer	• Modular and scalable structure	• Offers low efficiency at high stepping ratios
Resonant Converter	• Provides zero current switching	• Lacks galvanic isolation • Requires large LC tank
Hybrid Structure	• Modular and scalable structure	• High costs • High losses
Classical Structure	• Modular and scalable structure	• High losses • Requires high energy storage element (L) in case of buck/boost operation
DC-MMC	• Modular and scalable structure • Don't require internal transformer	• High filtering requirement • High stress on the SMs due to ac current circulation

V. CONCLUSION

This paper reviews the most efficient and state of the art dc-dc converters that are dedicated for applications in the multi-terminal dc grid. It classifies the existing topologies into two main categories based on internal isolation. Furthermore, the topologies in each category are discussed in detail and key advantages and major limitations of each design are summarized. This work has specifically focused on the converter topologies from the aspect of HVDC grid interconnection. For such application, high power density, dc fault tolerance, bi-directional operation and high reliability are important qualities of the most viable converter topology. From the detail analysis, it is concluded that the recent research mostly focuses on the designs that are scalable and modular in nature. For such reasons, the MMC-DAB is considered as the most suitable converter topology for the application of HVDC grids interconnection. It offers almost all the major qualities required for such application. Although, its cost is high as compared to other topologies, the concept of the combination of MMC and switches can be utilized in the near future for further advancements that can offer a reduced cost and better operation.

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