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REVIEW

Medium-voltage DC electric railway systems: A review on feeding arrangements and power converter topologies

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Abstract
Medium-voltage DC (MVDC) electric railway systems have several advantages over conventional DC and AC railway electrification systems. These advantages include higher capacity, possibility of connecting to power networks at lower voltage, removal of neutral sections, smaller line voltage drops, and longer distances between traction power substations. This paper reviews in depth the arrangements for MVDC railway electrification systems proposed in the technical literature and the topologies used for high-power medium-voltage AC-DC converters. With reference to typical requirements of a MVDC railway electrification system, the pros and cons of the topologies are critically analysed. Moreover, this paper reviews the DC-DC power converter topologies for on-board power electronic traction transformers, required to interface the MVDC power supply with the traction motors. Finally, the review highlights the existing challenges of MVDC electric railway systems and the potential areas of future research.

1 | INTRODUCTION

Medium-voltage DC (MVDC) electric railway systems have been widely proposed to address the typical limitations of conventional DC and AC railways. Unlike low-voltage DC (LVDC) railways, the spacing between traction power substations (TPSs) of MVDC railways can be much higher, thanks to the higher voltage level. Unlike AC railways, MVDC systems do not introduce imbalance on the AC utility grid [1] and can be connected to the widely available power distribution grids at lower voltage levels via cheaper and simpler connections. There is less voltage drop and reactive power consumption, as a result of less inductance in the MVDC railway systems [2]. Due to lack of skin effect, the MVDC overhead lines can be realised with simpler cable and wire layout. In addition, MVDC TPSs can be easily parallelled, reducing their power rating [1, 3]. There is no need for neutral sections, so power transfer to the trains is not interrupted. This means that the high-speed trains can maintain their speed [3]. MVDC TPSs can also be integrated into DC microgrids, facilitating the use of renewable power sources, energy storage systems and distributed generation units [1, 4].

The MVDC railways have not been implemented in industry yet, due to some technical challenges. For instance, the MVDC network should be controlled properly, avoiding undesired power circulation between TPSs. Protecting MVDC feeders against short circuit is another issue, as the DC circuit breakers are expensive and complicated [4]. Concerning the power converters used in TPSs and trains, the choice of topology is quite critical to ensure that energy efficiency and reliability are similar to components already in use, that is, transformer-rectifiers for DC railways and transformers for AC railways.

There are various proposals for implementing MVDC railways, which can be classified into two major approaches: the use of MVDC intermediate feeders for feeding LVDC or medium-voltage AC (MVAC) overhead lines; the use of MVDC overhead lines to directly feed the trains. Both approaches use AC-DC converters in TPSs to provide MVDC. In the first approach, the MVDC has mainly the objective of reducing transmission losses in comparison with conventional systems, while overhead lines and trains remain substantially unchanged. In the second approach, the trains use power electronic traction transformers (PETTs) to reduce the voltage of the MVDC power supply to levels acceptable for the traction motors.

To the knowledge of the authors, there is no comprehensive review on the proposed schemes for MVDC railways. Therefore, the aim of this paper is to review technical solutions proposed for the MVDC railways and discuss existing power converter topologies to assess suitable options for MVDC TPSs and PETTs in a feeding system with MVDC overhead lines.

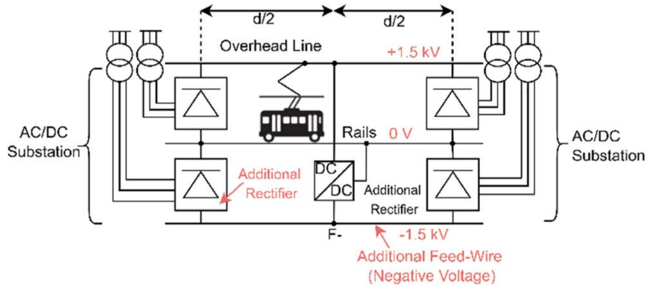

FIGURE 1 Three-wire arrangement for DC supply proposed in Ref. [5] with additional feed wire with negative polarity with respect to the rails

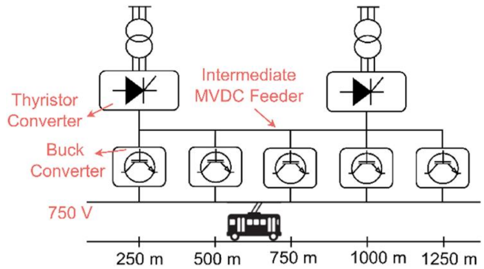

FIGURE 2 Feeding 750 V DC railway from medium-voltage DC (MVDC) feeder as proposed in Ref. [7]

2 | TECHNICAL SOLUTIONS FOR MVDC RAILWAY SYSTEMS

2.1 | Systems with MVDC intermediate feeders

A three-wire electrification system has been proposed in Ref. [5] to reduce the voltage drop, minimise power losses and increase the capacity of existing LVDC TPSs. The concept is similar to the AC supply systems with autotransformers and is realised by installing a third wire for transferring the power at double the nominal voltage level, while the trains are supplied at nominal voltage. Figure 1 shows the case where additional rectifiers are installed between the rails and third wire, and the third wire voltage polarity is negative with respect to the rails. Besides, multilevel DC-DC converters are used every few km to ensure that the train current returns through the additional feed-wire in a way similar to autotransformers for MVAC systems.

This configuration has also been simulated in Ref. [6] with voltages of 3, 6 and 9 kV DC for the third wire. Moreover, the power losses in feeders, contact lines and rails for different substations' intervals have been calculated and compared with conventional DC systems. In one study, the interval of two TPSs has been considered as 8 km, and the substation rectifiers and intermediate DC-DC converters have been assumed to be lossless. In this scenario, the average power losses for conventional 1.5 kV DC system have been calculated as 813.3 kW for a nominal power of 4500 kW. Using 3, 6 and 9 kV DC third wire and one intermediate DC-DC converter, the average losses reduce by 42.8%, 55.3% and 57.4%, respectively. However, the average losses for 3, 6 and 9 kV DC three-wire systems are still higher than the conventional 3 kV DC system. On the other hand, the study suggests that increasing the number of intermediate DC-DC converters in three-wire systems improves the efficiency. For instance, adding another intermediate converter to the 9 kV DC three-wire system decreases the power losses by 48.8% with respect to the case where there is only one intermediate DC-DC converter in the system. This is clearly dependent on the actual efficiency of the DC-DC converter that has not been considered in the study.

In Ref. [7], thyristor rectifiers have been proposed to feed an intermediate MVDC feeder, and fully controllable synchronous buck converters operate as TPSs and feed a traditional DC catenary, as shown in Figure 2 for a 750 V system. The simulation results for a load of 1 MW show that in comparison to conventional 750 V DC systems, the new configuration improves the efficiency of the feeding system (feeders and overhead contact lines) by up to 2% and reduces catenary voltage drop by up to 3%. The losses of the power converters, however, have been neglected in this study and will certainly reduce the benefits of the solution. The reference does not clearly mention the voltage level of the AC side and the MVDC feeder. Besides, the proposed system encounters some challenges including the control of circulating current between the buck converters and possible low-frequency power oscillation between the converters, which are not addressed in the study.

As another approach, supplying urban 750 V DC railways from MVDC distribution grid has been investigated in Ref. [8]. The proposed arrangement consists of a dual active bridge (DAB) converter that converts MVDC to LVDC and charging stations for electric vehicles in the railway TPSs. In urban railways, the substations are normally close to the train stations. Hence, the charging stations are located in the vicinity of transport hubs and can be used by electric vehicles such as electric cars and public electric buses. The charging stations enable the railway operator to utilise the electrification infrastructure during railway idle periods. This paper, however, gives no details about the control architecture, protection issues and other practical challenges.

In Ref. [9], the authors have proposed a configuration where a small number of high-power rectifiers are supplied by a HVAC grid to generate a multi-terminal MVDC bus alongside the railway. This MVDC feeder, shown in Figure 3, operates with the voltage level of 120 kV DC and can feed both DC and AC railways. The minimum distance between the rectifiers is 100 km. In case of AC railways, several inverter substations, located at distances smaller than the rectifiers, provide a suitable single-phase AC voltage for the overhead line. A possible realisation for the AC-DC converter has been also suggested, where several converter cells are connected in series at both AC and DC sides. Each converter cell consists of a voltage source converter (VSC), which is connected to a cycloconverter through a medium-frequency transformer (MFT). This topology, however, requires series connection of power electronic switches, and the paper does not describe it in detail. Moreover, undesired current circulation between the converters is a critical issue, which has not been discussed.

Ref. [10] has further evaluated the above proposal using a unified AC-DC optimal power flow model and an on/off control of DC-AC converters feeding the overhead line. In comparison to a 16 2/3 Hz, 15 kV MVAC system, a MVDC feeder would reduce the voltage drop of the catenary and reduce transmission losses. Furthermore, an optimisation problem has been formulated to determine the optimal control of the converters [11] to minimise total active power losses. The performance of MVDC feeder solution has been compared with both centralised and decentralised 16 2/3 Hz 15 kV MVAC systems, showing better voltage regulation and less power losses in the MVDC system.

A similar approach has been presented in Ref. [12], where modular multilevel converters (MMCs) are connected to 110 kV AC main grid and create a 160 kV DC intermediate feeder. Single-phase MMC inverters and step-down transformers are then used to feed the 27.5 kV AC railway electrification line. This arrangement benefits from high power quality, simple overhead line without neutral sections, modular design of power converters, and easy integration of renewable energy resources and energy storage systems, which can be connected to the MVDC intermediate feeder. However, due to high voltage level of the AC grid and the MVDC feeder, the number of required submodules in the MMCs are high, and step-down transformers are still needed on the railway side. In addition, the MMC rectifiers have been implemented with half-bridge submodules, which are unable to block the DC fault current. Thus, the system should be protected by MVDC circuit breakers, which are costly [4].

2.2 | Systems with MVDC overhead lines

MVDC overhead lines have been first proposed in Ref. [13], based on a monopolar multi-terminal radial network fed by 12-pulse thyristor converters. To keep reasonable insulation levels for the catenary, the system voltage has been chosen at 30 kV, similar to existing AC electrification systems. This feeding arrangement can limit the DC fault current by using controlled thyristor rectifiers. The paper has also proposed a design for locomotives with a simple line-commutated high-voltage inverter, an MFT operating at few hundred Hertz, a four-quadrant rectifier and a three-phase voltage source inverter feeding the traction motors. However, the paper gives no details on the design of controllers and especially how the fault current is determined and limited with acceptable time response. In addition, the high-voltage inverter installed on the locomotives has been implemented with thyristors, which require complicated commutation circuits.

Starting from the results of Ref. [13], a more practical solution with a new MVDC multi-terminal system is introduced in Ref. [1]. The proposed system uses VSCs as building blocks of the converters, which allow a better integration of the railway with distributed generation and energy storage units. As shown in Figure 4, various subsystems with different voltage levels can be connected to a 15–25 kV DC railway line as a distributed energy hub. In this paper, MMCs with half-bridge submodules have been proposed for TPSs, implying that the system should be protected by MVDC breakers.

The authors have also suggested two architectures for real-time control and power balancing in the MVDC network. The first is based on local VSC controllers and targeted at maintaining a constant DC voltage at the point of common coupling. The second proposal is to implement a central controller, where the DC voltage reference for each local controller is obtained from a droop function. The reference signal is inversely proportional to the substation output current. Moreover, a signal from a secondary central control loop is added to the DC voltage reference to optimise and coordinate the power drawn from the AC grid, considering the constraints of transmission system operator.

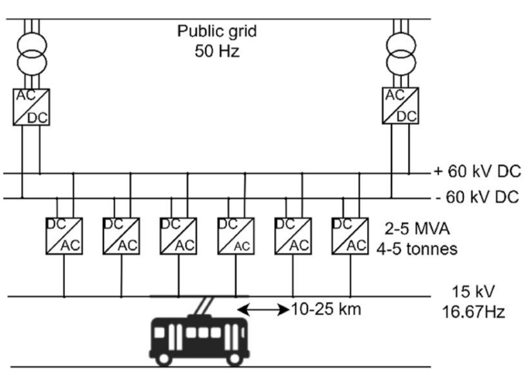

FIGURE 3 The multi-terminal medium-voltage DC (MVDC) bus concept proposed in Ref. [9]

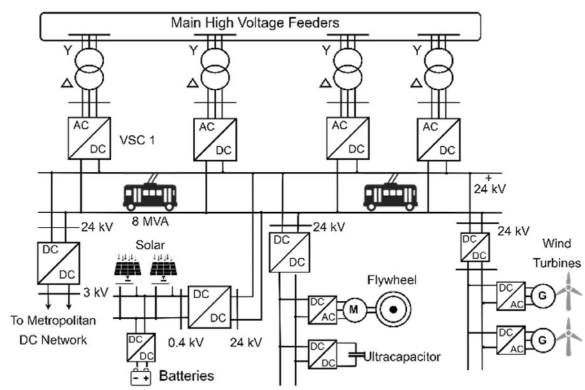

FIGURE 4 Proposed medium-voltage DC (MVDC) multi-terminal system [1]

In addition, two novel structures for rolling stocks, which are compatible with both 3 kV DC and 24 kV DC supplies, have been introduced. The first structure uses bidirectional isolated DC-DC converter implemented with multilevel VSC, MFT, and conventional VSCs. The second scheme has a simpler design, where two VSCs are connected to each traction motor in parallel. For 3 kV systems, the DC side of VSCs are connected in parallel, while for 24 kV DC supplies, a switch changes their connection to series. The paper has also shown by means of numerical simulations that the proposed system has higher capacity over a conventional 2 × 25 kV AC railway supply system while it benefits from the mentioned advantages of MVDC systems.

The concept of integrating electric railway systems into smart grids has been also described in Ref. [4]. Various structures for smart grids have been proposed, including LVDC, MVDC, and AC railway microgrids. Because of the aforementioned advantages of MVDC electrification systems and in particular, facilitating direct connection of distributed energy resources, implementing fast and ultrafast charging stations for electric vehicles and integrating LVDC systems such as metropolitan railways, MVDC railway microgrids have been considered as the most promising solution. The overhead line voltage should be in the range of 7.5–24 kV DC, which can be selected based on the existing infrastructure and regional and geographical conditions.

The authors of Ref. [2] have also proposed a simulation model to compare the MVDC catenary with autotransformer-based MVAC systems at mains frequency. The results show that the MVDC supply draws balanced currents from the three-phase grid and provides better overhead line voltage regulation in comparison to the MVAC system. Since the simulated MVDC system includes a droop control system, the power consumption is shared among the TPSs. In the MVAC systems, however, each TPS feeds the trains on its own section, as the feeding sections are electrically isolated. This increases the average power supplied by each substation, leading to higher power ratings for each MVAC substation in comparison to their MVDC counterparts. Furthermore, reactive power consumption in the MVDC system is limited to the transformer and AC side cables in TPSs, and this reactive power can be compensated by the TPS converters.

As another comparison, a simulation in which a portion of Paris-Lyon high-speed line operated in 25 kV AC is replaced with a 25 kV DC system has been reported in Ref. [14]. The results show that due to lack of inductance in DC systems and parallel operation of TPSs, 25 kV DC supply improves the voltage profile. Specifically, the catenary average and minimum voltage for the MVAC system are 23 and 18 kV, while for the MVDC system, are 25 and 24.5 kV. In addition, the average active power consumption decreases by 3.5% in the MVDC system. The analysis also shows that with the same voltage profile as the MVAC railways, MVDC substations can be located 30% further apart when they are feeding the same load.

The effect of the MVDC catenary voltage level on the overhead line cross-sectional area and spacing between TPSs has been investigated in Ref. [3]. This has been done for both suburban and high-speed transport services via a mathematical model, which considers the rail-to-ground voltage, pantograph voltage and temperature of the overhead line. Voltage levels between 1.5 and 10.5 kV with steps of 1.5 kV have been examined, and the results show that for voltages above 7.5 kV DC, both cable cross-sectional area and substation spacing are comparable with common AC systems.

Furthermore, a case study based on Paris-Strasbourg line with real data of traffic conditions has shown that a 9 kV DC system has the same performance of a 2 × 25 kV AC system, while having simpler power supply diagram and not requiring neutral sections and autotransformers. In this paper, however, the suggested topology for the TPS converters is a full bridge diode converter protected by high-cost solid-state circuit breakers.

Following this research, SNCF-Réseau has started a study to convert its 1.5 kV DC railway lines to 9 kV DC [15]. A strategy for replacing the DC railway supply system from low voltage (1.5 kV or 3 kV) to 9 kV has been introduced in Ref. [16] and is shown in Figure 5. In the first step of the evolution, the conventional rectifiers are still connected to the overhead line. However, some intermediate substations are replaced by a DC-DC power electronic transformer, which feed the low-voltage overhead line from a 9 kV feeder. At the final step, the voltage level of the catenary is raised to 9 kV, and all of the conventional rectifiers are removed. In this stage, power electronic transformers must be installed on the trains. A similar study on the Italian railway [17] has shown similar advantages for 9 kV DC systems.

The advantages of increasing the voltage level of DC railways up to 24 kV have also been discussed in Ref. [18, 19] in which their former study has investigated series connected 24-pulse current source converter (CSC) as the most efficient topology for the TPSs and has suggested the use of rolling stocks, working with both LVDC and MVDC voltage levels. However the TPS converter [18] and the train converter [19] have not been investigated in terms of performance and control.

Moreover, modelling and simulation of a double-end fed 24 kV DC railways with two TPSs have been presented in Ref. [20], as shown in Figure 6. In this study, a local control strategy is used, in which one of the TPSs is operated in constant power mode, and the other one is operated in constant DC voltage mode.

In the MVDC railway networks, there is the possibility of having circulating currents between the supply points. Therefore, it is important to implement a developed control scheme to avoid this situation. The control scheme can be even more advanced and incorporate conditions for which the circulation of current is intentionally sought, for example, to de-ice conductors for low temperatures or to create a parallel path between the nodes to ease congestion on the AC grid.

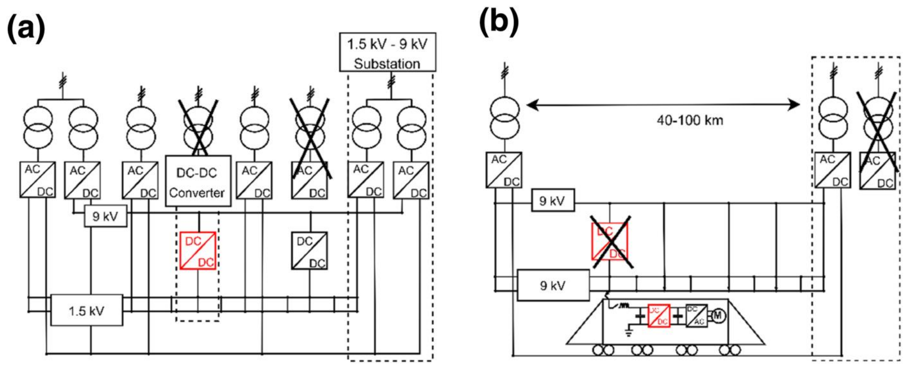

FIGURE 5 The strategy for changing the low-voltage DC to 9 kV DC supply proposed in Ref. [16]. (a) Low-voltage catenary along with 9 kV feeder and power electronic transformer and (b) 9 kV catenary and on-board power electronic transformer

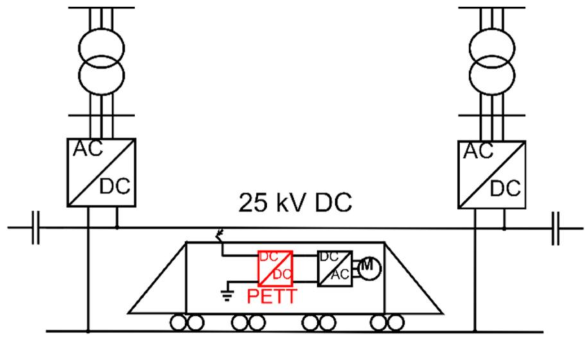

FIGURE 6 Double-end fed medium-voltage DC (MVDC) railway electrification system

3 | POWER CONVERTERS FOR MVDC ELECTRIFICATION SYSTEMS

3.1 | Converter topologies for TPSs

The topologies for MVDC TPSs can be classified into VSC and CSC families and are discussed in the following. All converter topologies include in the transformer to ensure galvanic isolation from the grid. This is because railway operator needs to maintain control on their grounding systems and the isolation reduce interference with other railway equipment, such as signalling.

3.1.1 | Voltage source converters

High-voltage, high-power VSC topologies, which can potentially be implemented in the MVDC TPSs, are shown in Figure 7.

For high-voltage application, a two-level VSC has been implemented for a small scale high-voltage DC (HVDC) transmission network with the voltage of 20 kV DC and power rating of 3 MW [21, 22]. At the AC side, this converter has been connected to 10 kV AC without a transformer. A large number of insulated-gate bipolar transistor (IGBT) switches have been connected in series to enable the converter to operate at high voltages. In order to turn on/off the series IGBTs simultaneously, a special gate unit has been designed. In addition, voltage dividers have been used to evenly distribute the voltage across the series IGBTs and decrease the switching losses. Adding these extra circuitries, however, increases the total losses, initial and maintenance costs, and the design efforts and decreases the converter's reliability.

Developing multilevel VSCs has provided new solutions to high-power applications, and they are extensively used in motor drives, static volt-ampere reactive compensators (SVCs), flexible alternating current transmission systems (FACTS), battery energy storage systems and HVDC transmission systems [23]. Multilevel converters in MVDC applications have been implemented to interconnect two asynchronous AC power systems with two back-to-back three-level neutral-point clamped (NPC) converters via a common 15.9 kV DC bus. The converters are responsible for reactive power support as well as active power transfer [24]. The NPC converter does not have a modular configuration and needs a large number of series semiconductor switches to operate at higher voltage levels, which leads to complex and expensive designs [23]. The voltage balancing across the elements in NPC converters is another challenge regarding their use at high voltages [25]. The active neutral-point clamped (ANPC) topology is similar to the NPC topology, and it has solved the unequal loss distribution problem in NPC topology by replacing the clamping diodes with IGBT-diode modules. The flying capacitor (FC) topology has also a similar arrangement to the NPC topology, where the clamping didoes are replaced with capacitors. The nested neutral-point clamped topology is a combination of NPC and FC topologies [26].

Multi-cell converters family have been proposed to avoid series connection of devices. Cascaded two-level VSC and cascaded three-level NPC are two members of this category. In these converters, shown in Figure 8, a number of two-level (three-level NPC) converters are cascaded, so each stage can be realised by low-voltage devices. The stages can be controlled independently, and thus the converter can reach to higher resulting switching frequency without increasing the actual switching frequency at the cost of more complicated control [27, 28]. The AC input for each stage, however, should be isolated from the other stages. This implies that the converter needs $N_{\text{Two-level}}$ transformers or a multi-winding transformer with $N_{\text{Two-level}}$ isolated secondaries.

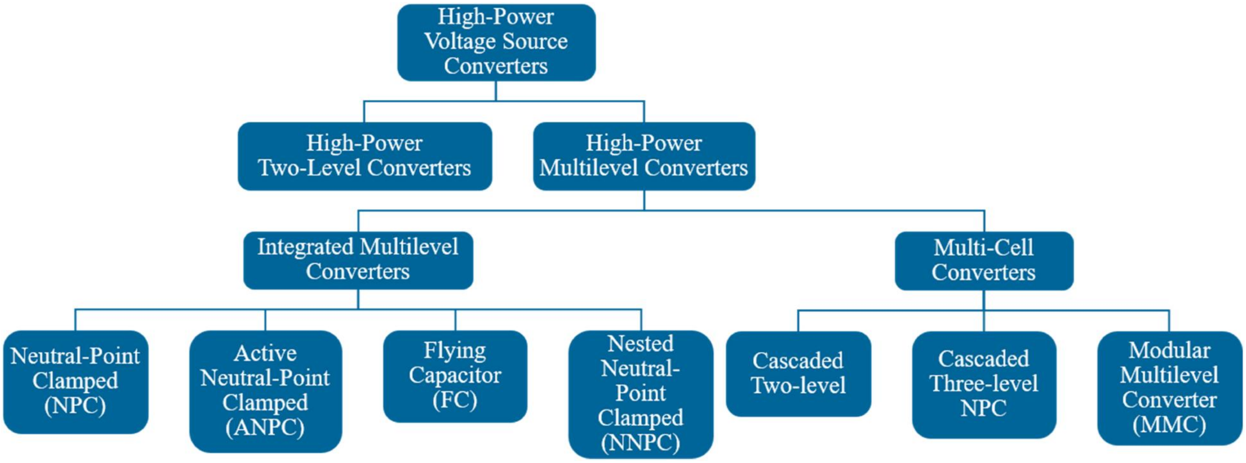

FIGURE 7 High-power VSCs for the 25 kV medium-voltage DC (MVDC) railway

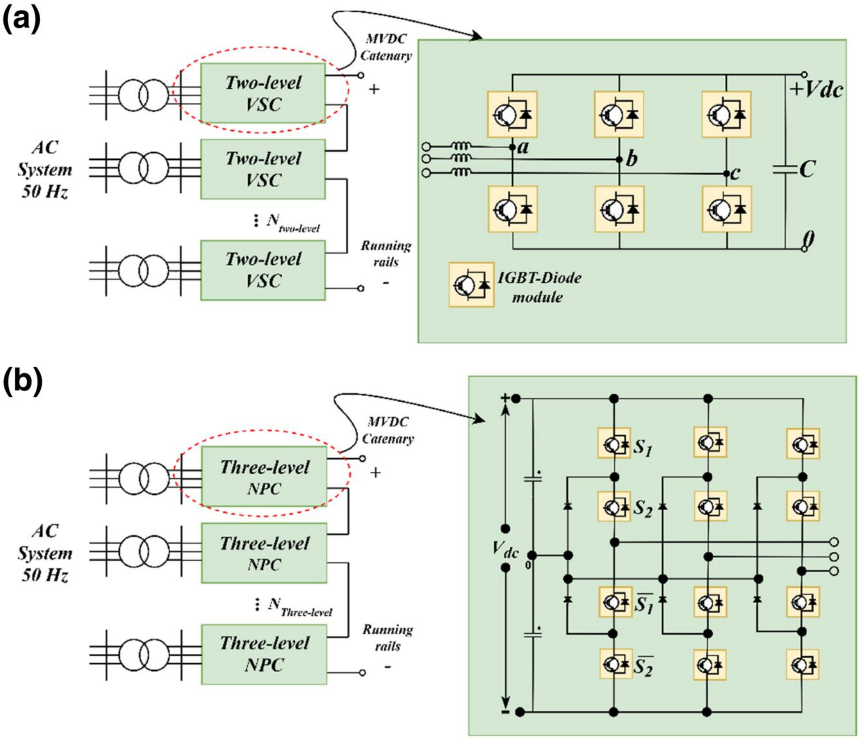

FIGURE 8 (a) Cascaded two-level converter and (b) cascaded three-level neutral-point clamped (NPC) converter

MMCs also belong to multi-cell converters family. Instead of cascaded converter bridges, MMCs consist of several submodules in each phase. The DC sources in submodules are not isolated and are directly charged and discharged through the common DC bus. Figure 9 and Figure 10 depict the MMC topology and various submodule arrangements. Comparison of well-known submodule arrangements for the MMCs is presented in Table 1. Table 2 presents several studies on using MMCs in MVDC applications. In particular, the performance of MMCs in 9 kV DC railways has been analysed by real-time simulations in Ref. [29], showing the feasibility of using MMCs in the MVDC railways.

In addition to the aforementioned submodules, there are other submodule arrangements with higher number of switches and higher complexity, which have been extensively compared in Ref. [30]. In general, higher voltage blocking capability, bipolar output voltage and symmetrical voltage levels are desirable for MVDC electric railways, but these characteristics are gained at the cost of higher number of components and consequently, higher cost and conduction losses, and lower reliability. In addition, the control design, mechanical structure of submodules and the protection schemes against internal faults are more complicated.

MMC and VCSs have been combined to form the alternate arm converter (AAC) [31], shown in Figure 11, in which several series connected IGBTs are in series of each arm of MMC to control the direction of the voltage. Using these director switches, the voltage rating of each arm is approximately

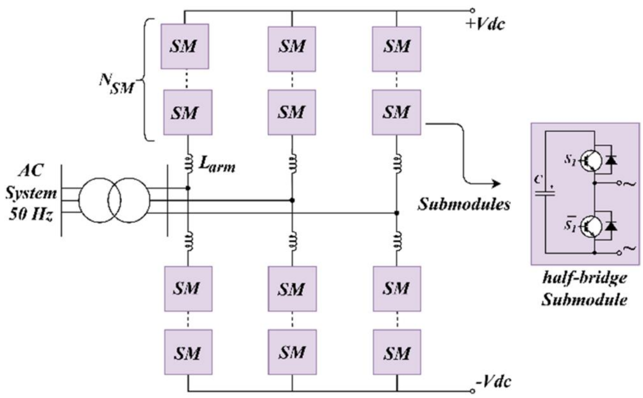

FIGURE 9 MMC topology and half-bridge submodule

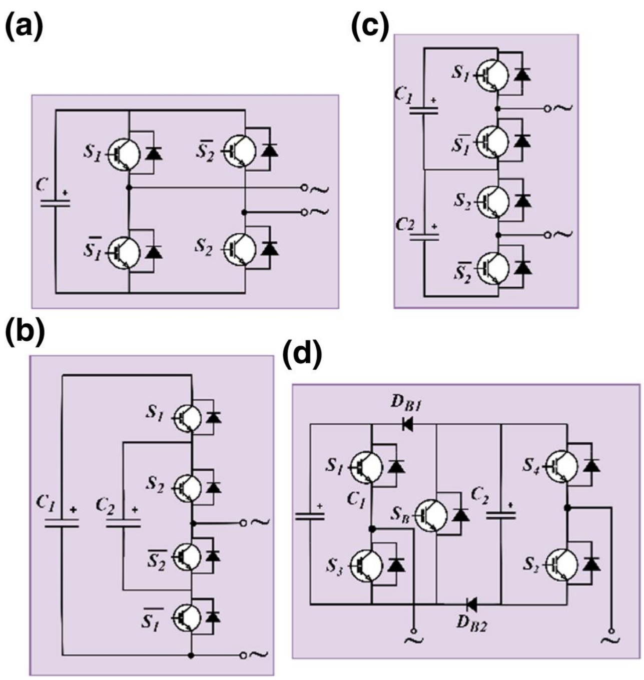

FIGURE 10 Submodule arrangements for MMCs. (a) Full-bridge, (b) flying capacitor (FC), (c) cascaded half-bridge, and (d) double clamp [26]

half of the voltage rating in a conventional MMC in normal operation. AAC is also able to block DC fault current as well as operating as static synchronous compensator (STATCOM) in DC fault conditions by adding more submodules. Nevertheless, the total number of IGBTs is less than a conventional MMC with full-bridge submodules.

Switching losses and the number of IGBTs of AAC can be optimised when the peak voltage of the AC side is about 27% higher than the voltage of DC terminals, that is, the DC voltage produced by each arm. In this situation, the converter operates in a 'sweet spot' condition because the energy storage devices work at their nominal ratings. In sweet spot conditions, director switches are switched at zero voltage (soft switching), which leads to reduction in their switching losses. However, this comes at the cost of losing the independent control of active and reactive power. Various methods have been proposed to address this issue at the cost of considerable increase in the voltage rating of the converter [30].

AACs benefit from the compact structure, lower number of submodules, soft switching feature and low switching losses, reduced number of active and passive elements, and very small or no AC filters. On the other hand, they suffer from series connected switches, higher conduction losses, and limitation on active and reactive power control [30].

3.1.2 | Current source converters

CSC family can be divided into two categories: load-commutated (LC) or line commutated converters (LCC), and pulse-width modulation (PWM) current source converters. In LCCs, widely used in railway electrification and HVDC systems, the semiconductor switches are commutated with the mains grid frequency (50 or 60 Hz). Conversely, the switching frequency is much higher in the PWM current source converters.

Diode and thyristor bridge rectifiers are the two types of CSCs already used in conventional LVDC railway electrification systems [38]. In order to reduce the DC voltage ripple,

TABLE 1 Comparison of submodule arrangements, as indicated in Ref. [26]

Characteristic	Half-bridge	Full-bridge	Flying capacitor	Cascaded half-bridge	Double clamp
Number of output voltage levels	2	3	3	3	4
Maximum blocking voltage of submodule	Vc[a]	Vc	2 × Vc	2 × Vc	2 × Vc
Maximum number of DC capacitors normalised to Vc	1	1	3	2	2
Number of devices normalised to Vc	2	4	4	4	7
Maximum number of devices in conduction path	1	2	2	2	3
Power losses	Low	Moderate	Moderate	Moderate	High
Design complexity	Low	Low	High	Low	High
Control complexity	Low	Low	High	Low	Low
Bipolar operation	No	Yes	No	No	Yes
DC fault blocking	No	Yes	No	No	Yes

[a]Vc is the capacitor nominal voltage in the submodules. For the submodules with more than one capacitor, Vc refers to the lowest nominal voltage among capacitor voltages.

TABLE 2 Studies on the use of modular multilevel converters (MMCs) in medium-voltage DC (MVDC) applications

Application	Submodule	Voltage level (kV) AC[a]	Voltage level (kV) DC	Power rating	# Modules (per phase)	# Switches (per phase)	Controls	Ref
MVDC distribution network	Half-bridge	6.6	12	1 MVA	16	32	Arm-balancing, AC current	[32]
MV rectifier for motor drives	Half-bridge	6.9	10.5	3.15 MW	22	44	AC and DC current, average capacitor voltage, circulating current, vertical and horizontal voltage balance[b]	[33]
MVDC distribution network	Not specified	6.6	10	7 MVA	20	Not specified	DC voltage, circulating current, AC line current, horizontal and vertical energy balancing	[34]
Ships with variable speed gas turbine (variable frequency at the AC side)	Half-bridge	4.16	10	25 MW	20	40	DC voltage, inner current	[35]
Power-hardware-in-the-loop facility—four MMC units	Full-bridge	3.3	6–24	1.25–5 MW	12 (in each individual MMC)	48	Branch current, AC current, DC short circuit current, and DC voltage controllers, individual cell energy and branch energy balancing	[36]
Flexible MVDC voltage source—two MMC units	Full-bridge	3.3	±5 to ±10	500 kW	16	64	DC voltage and DC short circuit current controller, inner voltage drop compensator	[37]
Inverter stage in an electric ship MVDC system	Half-bridge	220	6	150 kW	8	16	AC voltage controller, sorting algorithm, hierarchical redundancy strategy	[25]

[a]Voltage level for AC side corresponds to line-to-line root mean square voltage.

[b]The aim of vertical balancing is to equally distribute the stored energy between two arms of the same leg. Horizontal balancing aims to equalise stored energy in the legs [33].

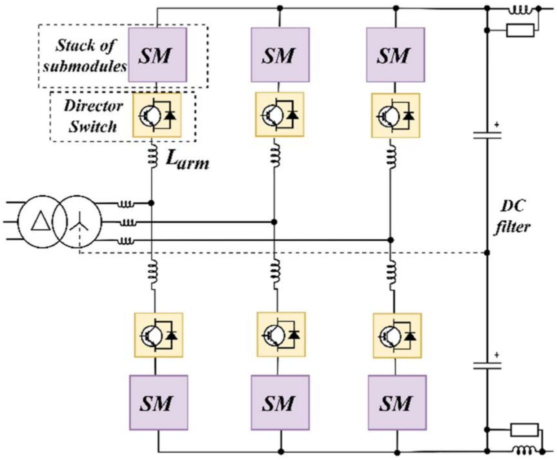

FIGURE 11 Alternate arm converter (AAC) [31]

improve the total harmonic distortion (THD) at the AC side and reach to higher output voltages and currents, several diode or thyristor bridges can be connected in parallel or series and form 12, 24, 36 and 48 pulse converters, and multiple winding transformers are needed to introduce the phase shift between the various AC inputs of the bridges [39].

Thyristor rectifiers can regulate the DC output voltage and, hence, increase TPS spacing. On the other hand, when the firing angle increases, the power factor reduces and the THD at the AC side and the harmonic content of the DC voltage both increase. Nevertheless, the AC side harmonics are within acceptable values defined in IEEE519 standard, and the DC ripples can be mitigated by capacitor filters [40].

The energy from regenerative braking of train can be sent back to the grid using reversible TPSs. To achieve this, a separate thyristor inverter is connected to the rectifier in anti-parallel configuration [41]. Another solution is to connect an active PWM converter to the rectifier. In braking mode, this converter operates as an inverter, while in normal mode, it operates as an active power filter for the rectifier [42].

For both diode and thyristor converters the input power factor cannot be regulated and if reduced by the presence of overlap, it increases with the load. Concerning DC side faults, CSCs can be designed to tolerate DC short circuits. In thyristor-based LCCs, the firing angle can be controlled to limit the DC fault current [43]. Furthermore, in force-commutated CSC topologies, a series connected diode is integrated with each semiconductor switch, enabling it to block the voltage in both directions. Hence, it can block the voltage that supplies the short circuit current. On the other hand, force commutated CSCs must be protected against open circuit faults using emergency current paths [44].

3.1.3 | Double-stage conversion

Another option for implementing high-power MVDC converters is to use double-stage conversion schemes. In these schemes, the AC input voltage is first converted to an unregulated DC voltage, then the DC voltage is regulated to the desired value. For instance, the use of single-star bridge cell rectifier as the first stage and DAB converter as the second stage has been described in Ref. [45, 46], and the use of diode rectifier connected in series with a boost chopper has been mentioned in Ref. [35]. The DAB topology is presented in Figure 12 for a fully bidirectional converter, but the second stage can use diodes if the power does not need to be reversed.

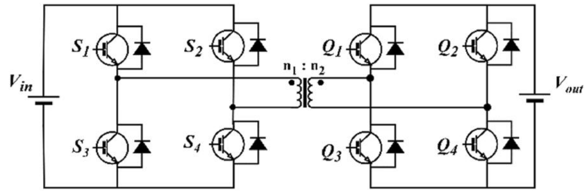

FIGURE 12 Dual active bridge (DAB) converter

In comparison to using a single high-power AC-DC converter, the double-stage conversion is less efficient and reliable due to the higher number of semiconductor devices. On the other hand, double-stage configurations with high-frequency transformers have a smaller overall size, which could be useful when the cost of land for the TPS is at a premium.

3.1.4 | Discussion on the topologies for the MVDC TPSs

A direct comparison between converter topologies is always difficult, as current and voltage stresses depend on the topology and often the design can be optimised for each different application. This section attempts at providing an indication of the component count of these topologies assuming that the same switching devices are adopted. The selected devices are chosen with the highest blocking voltage and current available at the time of writing the paper, considering that the typical converter ratings will exceed both in terms of voltage and power. The analysis is based on a reference case where the power output, the input and output voltages, and the overloading capability are those expected from MVDC systems or are equivalent to existing MVAC systems. Tables 3 and 4 show the selected specifications of the MVDC TPS and the semiconductor devices, respectively, used as a reference.

In the following and with the help of Table 5, the converter topologies are compared against criteria required by the MVDC railway electrification system, showing the compromise between the solutions:

- Power efficiency: The thyristor converters have lower switching losses and higher power efficiency compared to the VSCs. As indicated in Ref. [47], the thyristor-based converter designed for the MVDC railway has the power efficiency of above 99% when the DC current is between 30% and 450% of nominal load.

TABLE 3 Specifications of the medium-voltage DC (MVDC) traction power substation (TPS)

Specification	Power rating	Voltage at AC grid	Nominal voltage of catenary	Set point of DC voltage for the converters	Maximum voltage of catenary during long term overvoltages	Overload capability
Value	30 MVA	33 kV RMS	25 kV	27.5 kV	38.75 kV	450%

TABLE 4 Characteristics of the selected semiconductor devices

Semiconductor device	Maximum repetitive peak forward and reverse blocking voltage (V_{DRM}, V_{RRM})	Maximum value for the average on-state current $I_{T(AV)}$	Maximum value for RMS on-state current $I_{T(RMS)}$	Maximum collector-emitter voltage V_{CES}	Maximum DC collector current I_C
Dynex DCR3640H85 thyristor	8.5 kV	3.62 kA	5.69 kA	–	–
ABB 5SNA 1000G650300 HiPak IGBT-diode module	–	–	–	6.5 kV	1 kA
Infineon D4600U clamping diodes	–	–	–	4.5 kV	4.45 kA

- Initial capital and maintenance costs: The number of required components is an indicator for costs of a converter. For the topologies with series connected devices, the costs for voltage divider components are also added. Moreover, the number of required transformers also affects the overall cost and size of the converter. Table 5 reveals that the thyristor-based converter requires the lowest number of components among other topologies. Furthermore, modular topologies can be easily developed for medium- and high-voltage levels using identical modules, and this reduces the design complexity and maintenance costs.
- Reliability: In the case of failure in a module, it is possible to operate MMCs and AACs with reduced capacity instead of interrupting the power supply. This is also the case for cascaded converters if an IGBT-diode module or a stage fails.

Moreover, series connection of devices also negatively affects the reliability of thyristor-based converters, two-level VSCs, three-level NPC converters and AACs.

- Power quality and electromagnetic compatibility: Considering DC voltage regulation, all the topologies use DC voltage control loop. In general, the produced DC voltage by the VSCs has lower ripples in comparison to thyristor-based converters.

Similarly, the harmonic distortion of AC side currents is less in VSCs, so the AC side filters are smaller. The AC current quality is proportional to the number of voltage levels produced by the converter. Hence, the MMCs and AACs have the best performance. Moreover, cascaded topologies can be controlled with phase-shifted carriers, resulting in a higher AC current quality.

The use of high switching frequencies in VSCs also increases the possibility of interference with the track circuit signals. For instance [48], the magnitude of 5.1 kHz component in the DC voltage of a MMC-based MVDC TPS is 7.5 V. A typical range for operating frequency of track circuits is 4.75–16.5 kHz. Therefore, the component should be filtered out or the track circuit frequency should be adjusted to higher frequencies to avoid any interference. For thyristor-based converters, conversely, the interference is low.

- Requirements of multi-terminal DC (MTDC) systems: VSCs are more promising solutions than thyristor-based converters for implementing MTDC systems, providing redundant, reliable and flexible operation [49–52]. As an example from HVDC systems, the active and reactive power in VSC-based HVDC systems can be controlled independently and rapidly [53], which enables VCS-based HVDC to integrate weak and passive networks to the system [49]. In addition, the VSCs inherently have faster dynamic response [54]. Among VSCs, however, AACs have limitations in independent active and reactive power control, as discussed before.

3.2 | Converter topologies for PETTs

PETTs use MFT instead of line frequency transformer (LFT), which yields to higher power density and lower weight and volume. PETTs also feature high energy efficiency, controlled input and output voltages, currents, power flow, and load protection in case of line disturbances or imbalances. At the current state of the art, PETTs have been developed mostly for MVAC electrification systems, where an additional rectifier stage is needed at the input stage. Figure 13 shows the classical LFT traction transformers compared to PETTs in MVAC and MVDC systems.

The design of a PETT mainly depends on three key parts: medium-frequency isolation stage, medium-voltage input, and controllability. In order to connect PETTs to medium-voltage power supplies, different configurations have been proposed on the input side, especially the input series output parallel (ISOP) connection.

TABLE 5 Comparing topologies for use in the medium-voltage DC (MVDC) traction power substation (TPS)

Factor/Topology	12-pulse rectifier and inverter in anti-parallel configuration	Two-level VSC	Three-level NPC converter	Cascaded two-level VSC	Cascaded three-level NPC	MMC with full-bridge submodules	AAC (full bridge-short overlap period)
Number of semiconductor devices	168 thyristors	504 IGBT-diodes	504 IGBT-diodes/108 Clamping diodes	12 stages (504 IGBT-diodes)	6 stages (504 IGBT-diodes/144 clamping diodes)	12 submodules (1440 IGBT-diodes)	218[a] IGBT-diodes
Number of series components	9 thyristors in each 6-pulse bridge	12 IGBT-diodes	6 IGBT-diodes/9 clamping diodes	–	–	–	6 IGBT-diodes
Number of energy storage elements	1 L[b]	1 C	2 C	15 C	8 C	90 C/6 L	48 C/6 L
Transformer	1 × Three w[c]	1 × Two w	1 × Two w	15 × Two w	8 × Two w	1 × Two w	1 × Two w
Harmonic distortion of currents at the AC side	↑↑↑↑↑	↑↑↑↑	↑↑↑	↑↑↑	↑↑	↑	↑
Ability of limiting DC short circuit current	Yes	No	No	No	No	Yes	Yes

[a]Assuming that the AAC converter can block the DC short circuit currents and operates at sweet spot condition.
[b]L = inductor(s), C = Capacitor (s).
[c]W = windings.

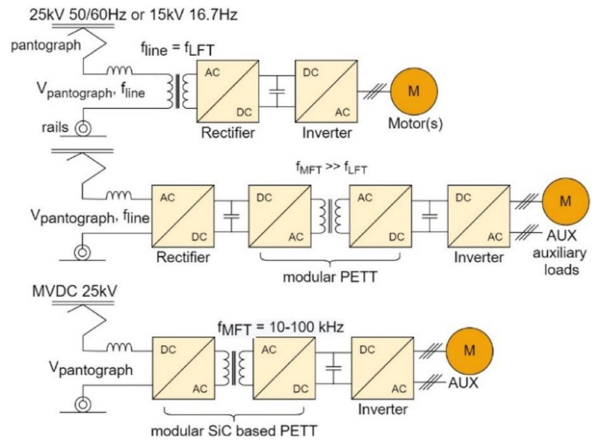

FIGURE 13 Comparison between line frequency transformer (LFT) and power electronic traction transformer (PETT) in medium-voltage DC (MVDC) and MVDC railway electrification systems

Based on state of the art, topologies for the PETT can be classified as shown in Figure 14. Depending on the location of the controlled stage, the traction converter can be either called isolated front-end, with the control stage on the low-voltage side, or isolated back-end converter, with the control stage on the high-voltage side.

In Figure 14, the four main MFT topologies are highlighted and each of them is illustrated in Figure 15. Single-cell traction transformers, shown in Figure 15a, were developed by Weiss [55]. Compared to modular and multilevel systems, they are simpler but with lower reliability. A single-cell traction transformer with NPC topology and 10 kV SiC metal oxide semiconductor field-effect transistors (MOSFETs) was recently proposed in Ref. [3].

The multi-cell structure proposed in Ref. [56, 57] is shown in Figure 15b. MMCs [58] simplify modules by eliminating the necessity of isolated DC supply for each, while keeping a cascaded structure [59]. Siemens developed a full-scale prototype of this topology, achieving high reliability, scalability to higher voltages and capability of dynamic voltage sharing. However, the high number of stages and levels showed increase in costs and losses, and a more complex and difficult control system [60]. To increase the efficiency, the number of cells need to be reduced, for example, using high-voltage SiC devices.

The semi-separated multi-winding (SSMW) MFT-based topologies, presented in Figure 15c, show feasibility at steady state and in different load conditions, robustness in control, independent output DC links in the secondary and multi-port configuration in the output stage, which facilitate an easier connection of different auxiliary loads and equipment as well as better bypass features. In addition, SSMW configurations present a matured and fully controllable modular design with balanced power distribution among the modules [60]. ALSTOM developed in 2007 a concept based on this topology, which they called 'e-Transformer'—a cascaded eight module propulsion system with a 5 kHz joint multi-winding transformer, obtaining 1.5 MW power and 50% weight reduction compared to classical LFTs [61]. On the other hand, the

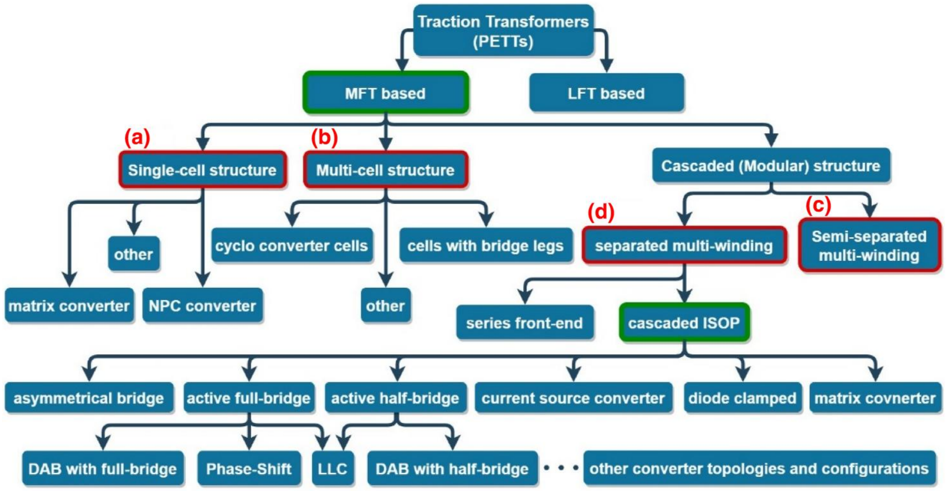

FIGURE 14 Classification of power electronic traction transformers (PETTs)

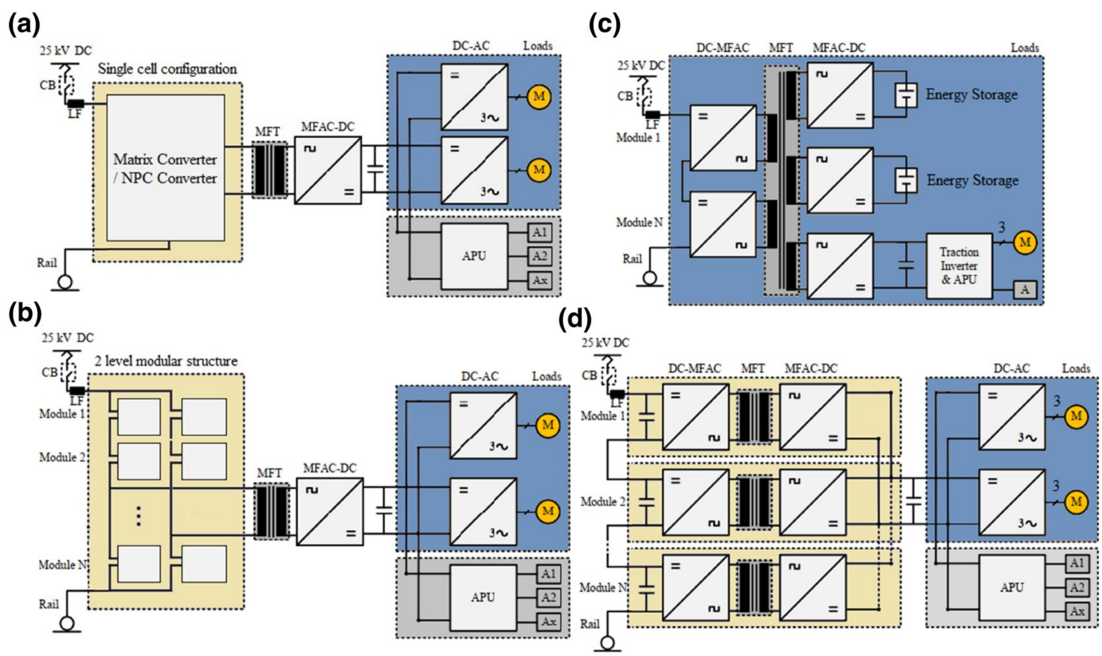

FIGURE 15 The state-of-the-art main power electronic traction transformer (PETT) topologies (APU: Auxiliary Power Unit; M: Motor). (a) Single-cell traction transformer, (b) multi-cell topology, (c) joint multi-winding transformer-based cascaded input series output parallel (ISOP) configuration, and (d) cascaded ISOP with separated multi-winding (SMW) transformers

control of cascaded topologies and the multi-winding MFT is complex, the power density is limited, and joint multi-winding MFT is difficult to manufacture and has weaker fault-handling and reliability capability.

Cascaded ISOP topologies with separated multi-winding (SMW) MFT, shown in Figure 15d, use separated windings (meaning that each DC-DC converter module has its own MFT) to overcome the major disadvantage of the previous topology. This topology can have different variations in the DC-DC converter stage, including active full-bridge converter topology, active half-bridge, asymmetrical active bridge topologies, diode clamped converters, and CSCs [60, 62]. The first example in the industry of a full scale PETT tested on a locomotive was developed by ABB—*a* 1.2 MW cascaded eight-module traction converter [63, 64]. The SMW MFT is less difficult to produce, and it has better fault handling capability and higher reliability as a result of more output stages in parallel. Although this structure needs more devices, which increase the overall costs, the higher initial investment is compensated by the higher efficiency and reliability.

In addition, high-voltage SiC devices can reduce number of modules and, thus, semiconductor devices [62]. Furthermore, inclusion of SiC devices in PETTs can lead to higher power density. As an example, Ref. [65] analyses the best trade-off among switching frequency, efficiency, filtering elements, noise pollutions and finally volume and mass. The paper presents an experimental test bench of a resonant single active bridge-based 300 kW PETT module prototype for a 9 kV MVDC railway system, investigating two types of 3.3 kV SiC MOSFETs, that is, 375 and 750 A Mitsubishi SiC MOSFETs. Currently, this first MVDC PETT is under development as part of FUNDRES project [66]. The two-module small-scale prototype capable of 600 kW power converts 1.8–1.5 kV, and at nominal power and switching frequency of 15 kHz, the prototype achieves 98.93% efficiency. In addition, experimental results for the two converter modules in ISOP connection have been reported.

In most traction converters developed recently, SMW modular ISOP topologies are favoured for their scalability to higher voltage levels and reliability. Regarding the design of the isolation stage, Ref. [67] analyses the technical design challenges and trade-offs of MFTs in high-power MVDC power electronic transformers. It also presents a design optimisation algorithm, which can generate different feasible MFT designs to obtain maximum power density, based on module requirements, available space, switching frequency, costs and materials. Furthermore, guidelines for choosing the optimal module number are presented. Another recent work [68] examines and classifies MFTs based on core material type, application areas, operating frequency and proposes another design methodology for power electronic transformers using finite element analysis software. However, other existing challenges in PETTs are protection against over-voltages, short circuit induced currents, isolation and thermal management issues [55].

4 | CONCLUSION

This paper has reviewed the proposed technological solutions for medium-voltage DC railways. There are two primary approaches to design the electrification network: (1) using intermediate medium-voltage feeders with low-voltage DC or medium-voltage AC overhead lines and (2) using medium-voltage DC overhead lines.

The paper has also assessed to what extent the topologies presented in the literature address the requirements of railway traction systems.

The investigations of high-power AC-DC converters for the TPSs and power electronic transformers have shown the advantages and disadvantages of the proposed solutions.

Some outstanding problems have been highlighted in MVDC railways, so Figure 16 shows the areas in which further research is considered necessary.

While control schemes [69–71], stability analysis [72, 73], and corrosion issues [74, 75] in MVDC railways have been investigated in the literature, interaction between the power electronic converters and signalling system, developing suitable protection equipment (e.g. high-current MVDC circuit breakers), and economic analysis need more attention from the researchers. For instance, a cost comparison between MVAC and MVDC railways helps to examine the feasibility and potential benefits of the MVDC railways.

The future direction of research in PETTs should be oriented towards the application of WBG semiconductors, to reduce the number of required devices in a multi-modular system and increase efficiency, without compromising the reliability.

FIGURE 16 Research areas in the field of medium-voltage DC (MVDC) railways

MVDC electrification systems are new to the railway industry. Therefore, there is need to develop new regulations and standards for their installation and operation. In all the mentioned areas, the developed knowledge from other MVDC networks (for example, MVDC distribution networks) can be used as the starting point for the design of future MVDC railway electrification systems.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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