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Review

Technical Review of Traction Drive Systems for Light Railways

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Abstract: Due to environmental concerns, governments around the world are taking measures to decarbonise railway transport by replacing diesel traction systems with cleaner alternatives. While the electrification of railway systems is spreading rapidly, it is unlikely that all routes will be electrified as the volume of passengers will not justify the high infrastructure costs. Therefore, it is expected that, for several lines, a combination of hydrogen and electric traction will be used, with the latter partly provided by fixed infrastructure and partly by batteries. Railway traction drives will then need to change to accommodate these new types of power supply. A detailed review of the available traction motors and drives is provided with this review, given application to the new hybrid-electric systems. In particular, permanent magnet synchronous motors with multiphase windings are evaluated in comparison with traditional three-phase machines. Additionally, low and medium-voltage multisource power converters have been reviewed, taking into account the introduction of wide band-gap semiconductor devices.

Keywords: traction drive systems; traction motors; power converter; fuel cell propulsion; wide band-gap devices

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1. Introduction

The electrification of transportation is crucial for transport stakeholders to meet existing policies of decarbonisation that have been issued by many governments around the world [1–4]. In this regard, the International Railway Association (with 240 members worldwide) has two main objectives: reducing emissions by 2030 and switching to more sustainable traction modes by 2050. The first objective will be addressed by improving the energy management systems, while the second objective will be achieved by a modal shift scenario that involves shifting the transport of goods and passengers from road to rail, which may lead to greenhouse gas (GHG) reduction by duplicating railway passengers within the transport sector [5].

Diesel trains have higher emission levels and are noisier than electric trains. However, the electrification of railway lines has a high capital cost, and it is unlikely that all routes will be electrified. These considerations suggest that hybrid trains, i.e., those capable of travelling both under the wire and independently, will see a substantial development over the next few years. For these reasons, batteries and hydrogen fuel cells are currently considered the most viable alternatives to railway electrification [6].

Electric and non-electric traction systems are combined in hybrid traction systems [7]. Diesel–electric is a popular type of hybrid propulsion because it does not need a gearbox for power transmission [8]. Electric motors offer better torque performance in the whole speed range and only need a fixed-ratio gearbox [8]. When tank-to-wheel analysis is taken into consideration for the traction system, Battery–electric, battery–fuel cell, battery–fuel cell and electrified systems are the greener options and are being investigated extensively nowadays. The main target of the combination of battery and hydrogen propulsion is to achieve a low-carbon-emission alternative to diesel. When using batteries with fuel cells, they provide direct electrical power and operate at higher efficiencies than internal combustion engines.

For traction motors, power density and efficiency are the key properties for railway applications. The most widely used traction motors are induction motors, but there are still a large number of DC motors and synchronous motors in legacy systems, and now, permanent magnet synchronous motors have emerged for several new applications [9,10].

Traction converters are classified as DC/AC-fed, current and voltage source inverters for AC motors, which will be investigated in this article. In addition, power converters can be classified for vehicular applications as medium-voltage converters or low-voltage converters, with unidirectional, bidirectional and multilevel topologies [11]. Additionally, references [12,13] investigated a cascaded resonant DC/DC converter and a transformerless conversion unit for a light DC railway, respectively.

This paper reviews in detail the main traction drive systems used in independently powered trains, with a focus on the comparison between permanent magnet synchronous traction motors and induction traction motors. Additionally, the number of motors with dedicated converter arrangements is surveyed to understand the overall volume and weight of the traction drive system. Then, conventional power converter units are reviewed considering the recent introduction of wide-bandgap (WBG) equipped converters that promise a significant increase in the energy efficiency of the traction system.

2. Traction Drive Systems

2.1. Diesel Traction Systems

Diesel-only traction systems have been considered mainly for single railcars [14], as diesel engines are not sufficiently reliable and powerful for railway traction [15]. Dependency on diesel fuel, the level of CO_2 emissions and the overall efficiency of the diesel engine are considerable negative aspects of the traction system. Recent studies have focused on reducing emissions, especially those of hydrocarbon waste, NOx and CO [16]. These pollutants can be reduced by using greener fuel types, such as oxygenated fuels, biofuels, biodiesel, alcohols, vegetable oil, acetone–butanol–ethanol blends, dieselhols (blends of types of diesel, biodiesels and alcohols), water–diesel emulsions, etc. Some blended fuels release more NOx and have a lower energy content, making them more costly [17].

Amongst the blended fuels, biofuels are interesting for the railway transport sector due to the reduction of greenhouse gases, unburnt hydrocarbons, CO and particulate matter with the reduced increase of NOx [17]. Biofuels are compatible with ordinary diesel engines, with only minor modifications [18]. They have also been proposed in combination with fossil diesel without engine modification, which requires water-blended fuels, such as water taker apparatus, wear minimisation system and oil contamination structure [17].

2.2. Electric Traction System

Independent powered electric traction has been introduced to increase train performance by removing the power generation unit from the train. The main advantages of catenary-free electric traction systems can be listed as:

- ✓ There are no emissions at the point of use;
- ✓ Lower maintenance costs;
- ✓ Regenerative braking to reduce energy consumption;
- ✓ Lower electrified-track capital cost investment compared to electric-only traction.

The disadvantages are:

- $\mathcal{X}$ They require a larger onboard energy storage system;
- $\mathcal{X}$ Complex energy management;
- $\mathcal{X}$ The cost of capital for an energy storage unit is high;
- $\mathcal{X}$ Power interruptions affect services;
- $\mathcal{X}$ Interference with command, control and communication systems.

Figure 1 shows the battery with an electrified multiple unit configuration, which uses the catenary system to charge the battery and can reach an area where an overhead installation does not exist due to the battery unit. In [19], its efficiency and regenerative braking were reviewed and compared with diesel multiple units.

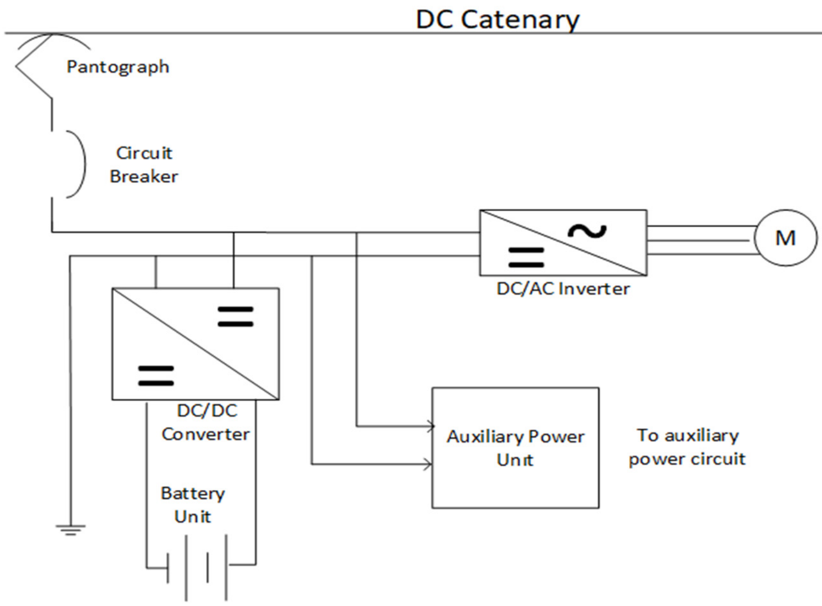

Figure 1. Electric with battery traction system [20].

2.3. Hybrid Traction System

Hybrid systems can be classified as fuel cell hybrid systems and diesel–electric systems.

A diesel–electric traction system uses a diesel engine to drive an electric generator, which then sends electricity to the traction motors, as illustrated in Figure 2.

By replacing the fixed gear ratio with mechanical transmission, diesel–electric traction has been used successfully since the 1920s [21] to overcome the problems of mechanical transmissions, which allows the gear ratio between the engine and the drive wheels to change as the vehicle speeds up and slows down [22]. On the other hand, diesel–electric traction combines the advantages of electric machines and diesel engines. Diesel–electric traction has lower emissions than diesel-only traction, better working performance and higher reliability [23], since this configuration increases the diesel engine's lifespan and provides better starting torque with electric transmission.

Existing studies have investigated the application of energy storage systems (ESSs) to increase efficiency and reduce CO_2 levels. ESSs can be used to either reduce the peak power of a diesel engine or reduce fuel consumption.

Nickel–cadmium (NiCd) batteries have been used for peak-shaving operations for shunting locomotives [24] by providing up to 25% of the demanded power. The Li-ion batteries proposed by [25] have shown a reduction of 16.5% in fuel costs. In [26], flywheels showed a similar reduction of 16.65% of fuel consumption. Both batteries and flywheels are pre-charged by either the electric power network or regenerative energy. The main benefits derived from this configuration are the reduced use of fuel and NOx emissions, which are cut by 30% [27].

Recent proposals focused on how to improve the recuperation of the braking energy in the ESS [28], as shown in Figures 3 and 4. As stated earlier, this excess energy can be stored most efficiently in flywheels, supercapacitors and batteries for railway applications. Ref. [29] addressed the solution overcharging or discharging problem of a $LiFePO_4$ battery pack by implementing the state-of-charge estimation algorithm based on the lookup table approach. In [30], the authors proposed high-speed flywheels to mitigate high-self-discharge problems depending on the load profile. The effect of the distance between the supercapacitor and the traction substation was elaborated in [31], then [32] included a control strategy with a variable threshold for trackside energy storage systems. Additionally, Ref. [33] provided a case study that used trackside flywheel energy storage and proposed a modified nodal analysis method based on train movement and electrical-network load-flow simulation. The results showed that energy recuperation increased at the overhead line.

In [26], the flywheel storage mechanism was employed to replace one of the diesel–electric locomotives as the intermediate energy power plant for three diesel–electric locomotives. In [34], the authors evaluated onboard and wayside energy storage systems to optimise energy consumption and increase performance.

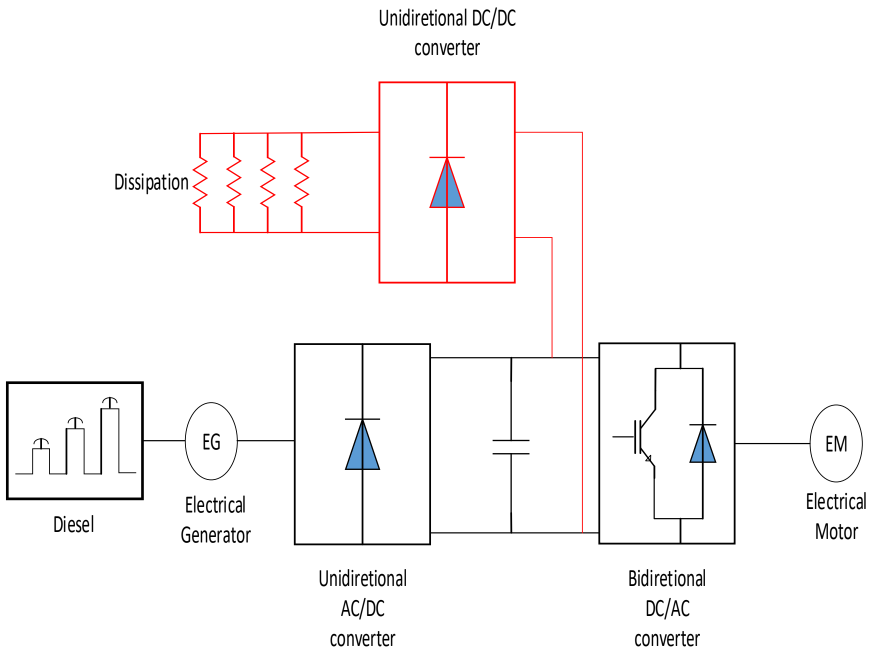

Figure 2. Schematic of diesel–electric power conversion chain with dissipation resistors [35].

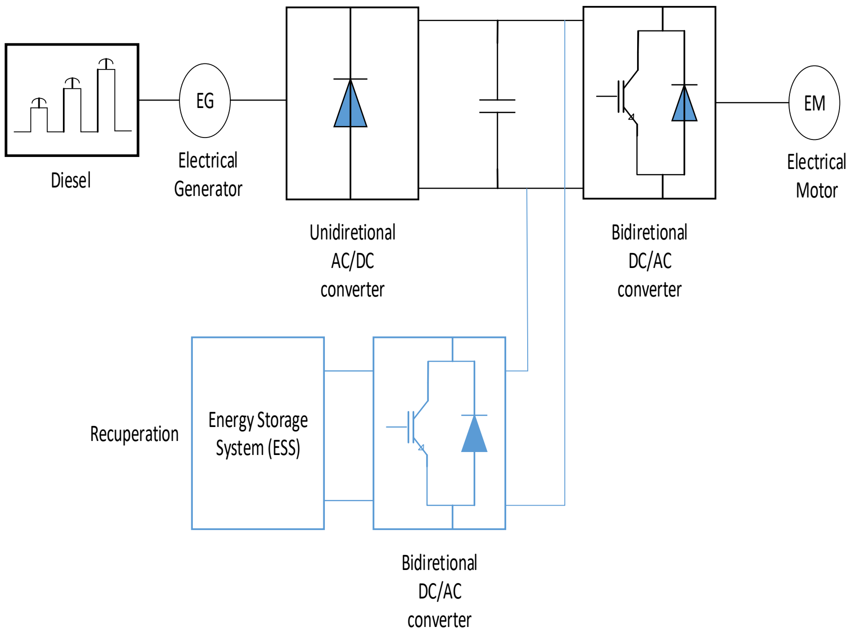

Figure 3. Block diagram of diesel–electric traction with an energy recuperation system [35].

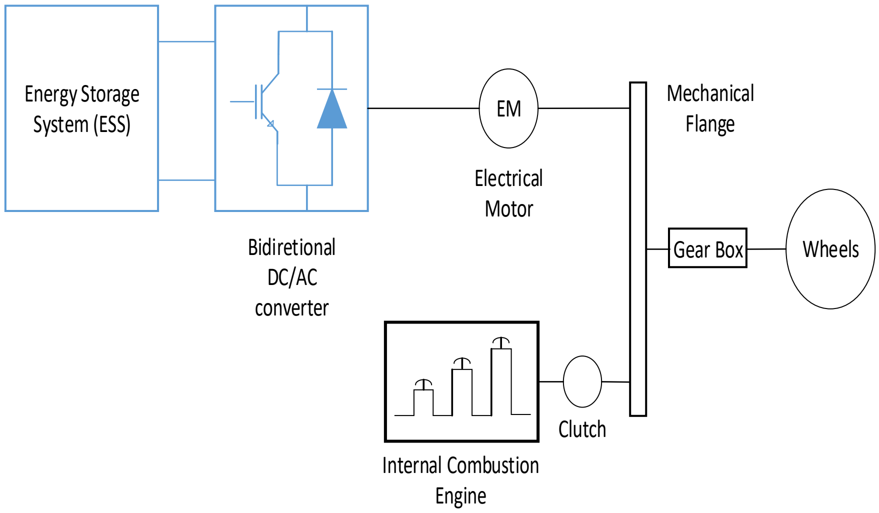

Figure 4. Parallel hybrid diesel–electric traction system [36].

Diesel with batteries is used in JR East Ki-Ha E200 and JR Hokkaido [37,38] as well as [36] as hybrid diesel cars. The main targets are the regeneration of energy and reducing the emission level by using a series hybrid system that stores the braking energy efficiently within two sets of batteries. Therefore, the diesel engine is operated and controlled by the secondary battery at its most efficient point.

Hybrid diesel traction is shown in Figure 5 and consists of a diesel generator and a catenary connection [39]. It is becoming less costly and has been discussed in literature in terms of fuel consumption [25] and architecture [40]. The existence of a battery storage unit enables one to scale down the engine size, which then requires less fuel and becomes more efficient with variable SOC references by using the algorithm given in [25]. Additionally, mild, parallel hybrid and series hybrid architectures were analysed in [39] to reduce both powertrain cost and fuel consumption. Mild powertrain architecture enabled us to save 14% on fuel in the case used for comparison.

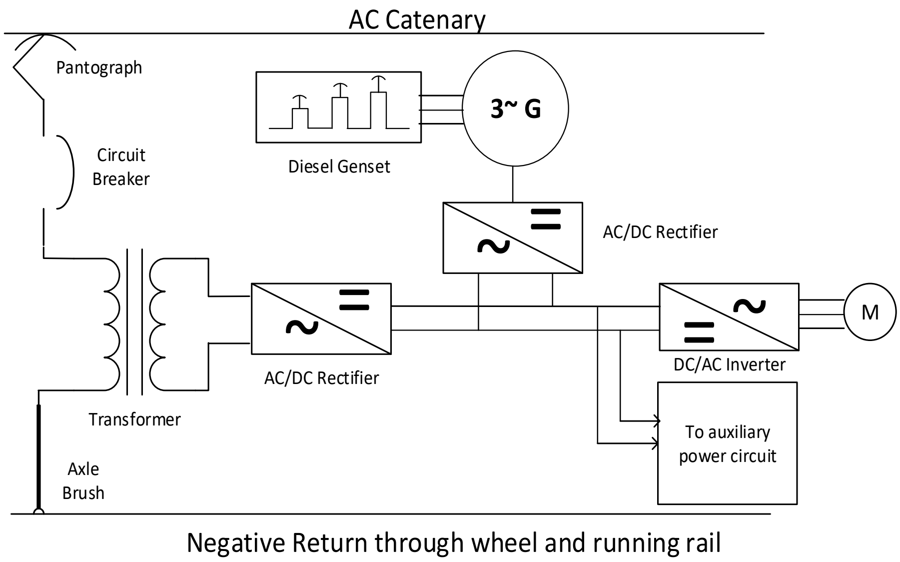

Figure 5. Hybrid diesel–electric multiple-unit system [39].

In another aspect, the fuel cell with battery system in Figure 6 is utilised more effectively as a hybrid traction system. For the example configuration, the battery unit can be connected in parallel to the fuel cell and supply energy during start-up and acceleration, as well as store energy during regenerative braking. In most circumstances, a fuel cell is designed for the train's average power demand, while a battery is designed for peak power and regenerative braking [19].

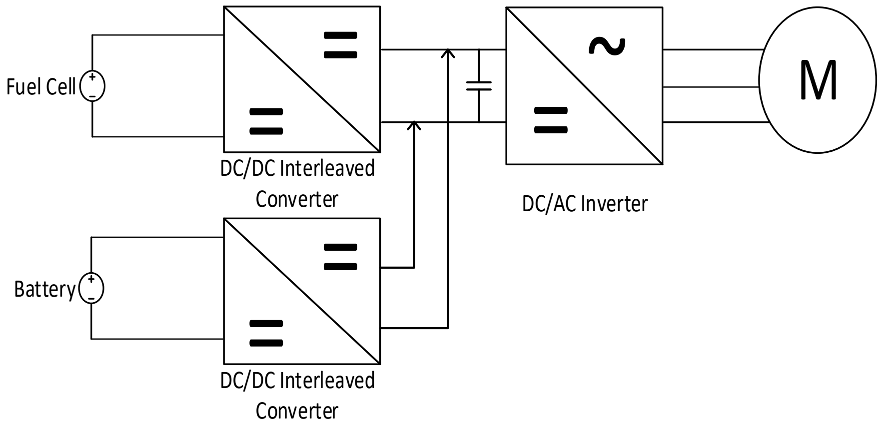

Figure 6. Fuel cell–battery hybrid traction [19].

By comparing the fuel cell with an internal combustion engine (ICE), the following statements can be derived according to the efficiency power maps given in Figure 7.

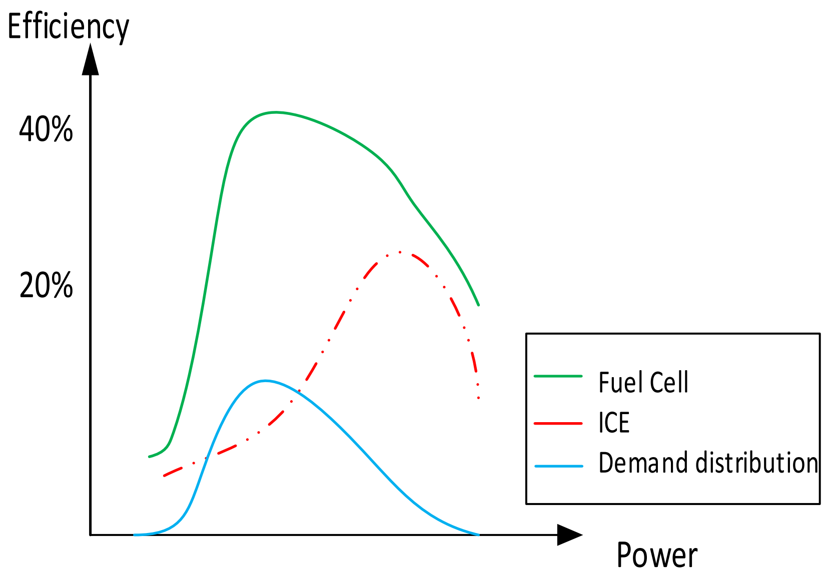

Figure 7. Fuel Cell & ICE Power Efficiency Curves [41].

- The fuel-to-wheel efficiency of the fuel cell is 40–50%;
- The fuel cell operates at its maximum efficiency of around 20–30% of its rated power, but can be increased up to 60%;
- The diesel ICE efficiency is 20–25% and a maximum occurs at 70–80% power;
- Fuel cells have better efficiency maps for driving power demands [41].

3. Traction Motors and Arrangements for Railway Applications

Although DC motors and wound-rotor synchronous motors (WRSMs) are still available on several trains, they are mostly legacy systems and will not be covered in this review, as the vast majority of recent research has focused on induction motors, permanent magnet synchronous motors and improved WRSMs, such as brushless WRSMs in several studies.

Although PMSMs' magnetic material costs and the demagnetising issue of the magnets are clear disadvantages, some studies have addressed the demagnetising issue of PMSMs and enabled them to have an equally distributed demagnetised field to achieve a smooth torque transition [42–45]. Most of the researchers adopted particular software to overcome the problems, despite the large amount of research having been carried out on this topic [46–48]. However, the cost of magnetic materials is still a problem, since one country is holding the market due to having all the rare earth element reserves. Therefore, brushless WRSMs have also been studied and used for modern railways recently to overcome the deficiencies of the WRSMs and provide a wider speed spectrum. However, this motor uses the third harmonic current to create a voltage across the rotor windings, which leads to high harmonic distortions and then develops ripples in the machine's electromagnetic torque [49]. In [50], the authors proposed a configuration that employs stator harmonic windings, a transformer and a diode rectifier circuit to reduce the torque ripple, but it became bulky. For this reason, thyristor-controlled stator harmonic windings have emerged by offering smaller sizes and cheaper solutions, as explained in [51]. On the other hand, having rotor windings will result in rotor losses, and the speed of the motor might be restricted by rotor windings, as well as the rotor integrity.

There is also another important feature of electric motors called the constant power speed range (CPSR). The speed capability of an electric motor can be extended by using the field-weakening technique, but there are still restrictions on the limits of the motor. For instance, the CPSR is four or five times the rated speed of an induction motor [52], while this is five times for PMSMs [53]. This speed range can be extended by the optimisation of the reverse-salient permanent magnet synchronous motor up to 7.25 times that of the rated value [53]. Additionally, the constant power region was monitored for brushless wound rotor synchronous machines (BWRSM) in [54] and the speed was extended from 900 rpm, the rated value, to 3500 rpm by using the injection of a negative id current.

Eventually, this is a trade-off to utilise traction motors that possess different advantages and disadvantages. In this regard, the paralleling of IM and PMSMs utilising fewer inverters is reviewed.

3.1. Permanent Magnet Synchronous Motors

The current traction motor trend is to use PMSMs and advanced control algorithms to improve system reliability [55].

Although the main requirement for traction motors is to require less maintenance, recent studies have focused on increasing the efficiency of traction motors. Therefore, induction motors were adopted by designers for the purpose of reducing maintenance costs, but PMSMs are more efficient. For the efficiency target of PMSMs, entirely enclosed self-cooled PMSMs for narrow gauge trains were explored and tested in [56].

The main benefits of PMSMs are their energy-saving features and their high level of power density. For instance, 200 kW PMSMs have 97% efficiency, while their induction machine counterparts have 92% [57].

There are few PMSM manufacturers for railway applications, as shown in Table 1.

Table 1. Selected light railways using permanent magnet motors [8].

Operator	Trains	Manufacturer
SNCF	31xCitadis-Dualis tram-train vehicles	Alstom
Praha	15T For City low-floor tram	Skoda
Prototypes and Other Test Trains		
München U-Bahn	C19 metro trainset with Syntegra bogies	Siemens
China	Fuel cell loco prototype	CNR Yongji
Turkey	Citadis X04 low-floor tram	Alstom
Japan	Gauge-Changing Train 2	n/a

The stator windings of permanent magnet machines are quite sensitive to failures, accounting for 50% to 90% of all failures of the machines [55–58]. There are several reasons for the winding failure of permanent magnet motors, causing the deformation of electrical insulation, which is affected by the resistive and capacitive features of the machine.

3.2. Paralleling the Motors

For railway applications, induction motors can be paralleled and fed by one inverter. The volume and cost of the traction system are reduced by paralleling multiple motors with one inverter. However, this case is not possible for synchronous motors.

It is worth mentioning that [59] proposed double-layered winding induction motors for railway traction to enable the motor parameters to be nearly the same for the paralleling purpose. A multi-machine drive system for both induction machines and permanent magnet synchronous machines used in electric multiple units was investigated in [60] in terms of a highly reliable traction system. Then, open-end-winding PMSMs were considered an alternative for the paralleling of PMSMs. Additionally, Ref. [61] indicated a load sharing problem with paralleling motors, which happened because of the fact that they do not have identical wheel sizes powered by parallel machines.

Some studies also referred to the paralleling of motors for electric vehicle applications, which might be useful to consider for railway applications. For example, Ref. [62] provided a control technique for hybrid electric vehicles that utilised IM and [63] addressed how employing two inverters can upgrade the efficiency of IM by extending the constant power region. Furthermore, a six-phase IM with a pole-changing technique was adopted in [63,64] to keep the volume within the acceptable margins while broadening the constant power region.

Paralleling two PMSMs is quite difficult because of the non-coincidence of the pole positions of multiple motors, which are unable to control the current of multiple motors simultaneously. Hence, losing the synchronism results in torque pulsations [65,66]. Most of the research has addressed how to eliminate this torque ripple for paralleled permanent magnet motors, such as damping control studied in [67], the five-leg inverter utilised in [68,69] and the nine switch inverter proposed in [70,71]. Every single one of these solutions has drawbacks, namely limited inverter output voltage, requiring voltage balancing technique, low voltage ratio due to sharing the DC-link voltage between the motors, etc. Additionally, to limit torque vibration, Refs. [72,73] drawing attention, a driver uses an extra inverter and motor windings.

To be able to understand the difference between the utilisation of PMSMs, IMs and the effect of paralleling the motors on the overall volume and weight of the traction system, a lightweight, four-carriage with eight-motor railway case study [74] was taken into consideration. Two similar datasheets [75–77] were used for 200 kW motor dimensions for the sake of a fair comparison of IMs and PMSMs. The volume and weight of the traction drive system are compared in the following charts. It is quite obvious that the inverter volume and weight are reduced in the paralleled IM case due to feeding two motors from one inverter, but PMSMs are more power-dense than IMs based on the analysis given in Figure 8. The overall comparison of the traction drive size is illustrated in Figure 9. Hence, PMSMs offer fewer volume and weight options, which means more efficient paralleling of two motors.

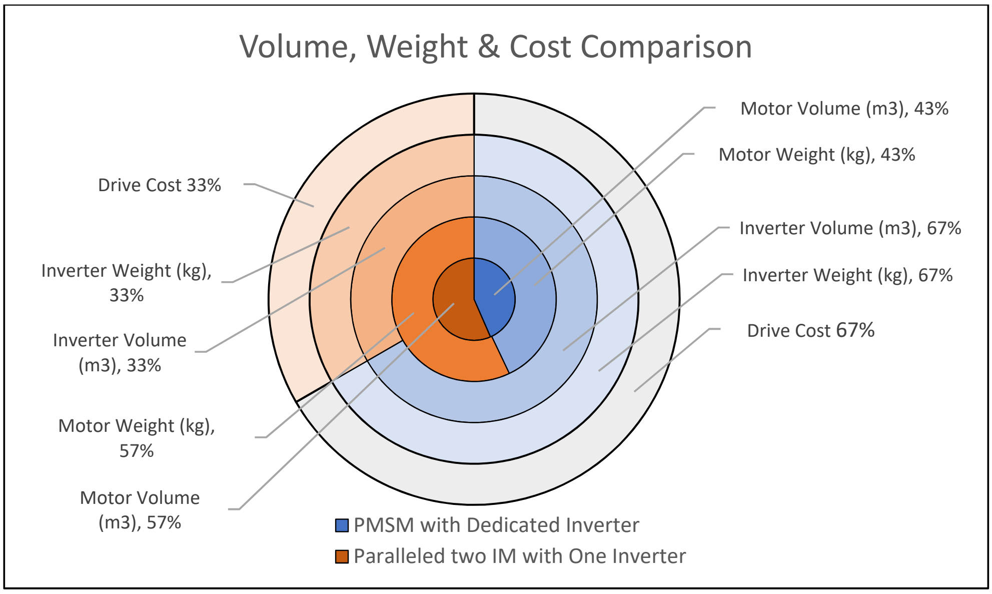

Figure 8. Volume and weight comparison charts for two configurations.

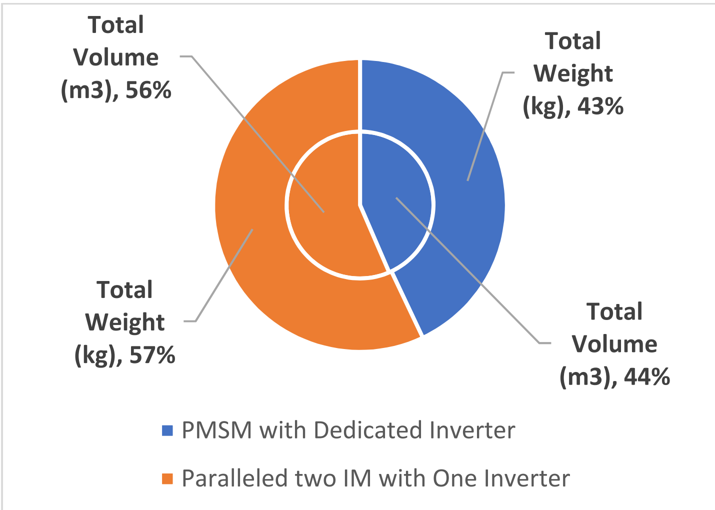

Figure 9. Overall volume and weight comparison.

3.3. Multiphase/Multi-Three Phase Structure

Despite the wide usage of three-phase machines, multiphase machines have been gaining popularity recently. The main reason for the interest in multiphase machines is their reliability, which has crucial importance, particularly for aerospace and traction applications. These machines also have other benefits, such as the lower rating of their drive circuits' components, lower harmonic distortion and lower total losses when compared to three-phase machines [78].

The other purpose of the multiphase/multi-three phase system is to make the machine windings electrically and magnetically independent to eliminate the interaction of the two or more three-phases with one another in failure. This means that one-phase breakdown does not affect the system [78]. The potential options for six-phase PMSM configurations are summarised here.

Two design ideas are common for six-phase machines according to the connection of the neutral point and phase displacement angle. In [79], dual-three-phase (0°), asymmetrical six-phases (30°) and symmetrical six-phase (0°) machines were investigated in terms of their phase displacement angle. It should be noted that dual three-phase machines are known by different names, such as asymmetrical six-phase, split-phase, or double-star machines, in many studies [80]. Therefore, the name of the asymmetrical machine is accepted as a dual-three-phase machine in this article.

As for open-end winding configurations, the most important benefit is fault tolerance when compared to their one-side powered counterparts. This topology pursues operation during the breakdown of one of the inverters or DC suppliers [81]. Additionally, the voltage is halved by using this configuration, since each winding group is energised by individual inverters located on both sides. Additionally, an extra semiconductor and passive components, such as capacitors, diodes, etc. are needed in multilevel converters to enable voltage balancing techniques. Nevertheless, the open-end topology makes the system simpler by reducing the number of passive components due to having two individual energy suppliers [79,82]. Furthermore, the extenuation of the odd-numbered harmonic content owing to the 30° phase displacement angle of the input voltage is another benefit of the open-ended configuration [83].

It is well-known that the current back-EMF of an electrical machine can remove the harmonic content in the associated currents. As a result of the lack of these back-EMF currents, massive deteriorations show on the current waveforms. Henceforth, both the availability of $6n \pm$ first harmonic components and the inexistence of current back-EMFs will be a handicap of the six-phase machines [84]. As previously stated, an open-ended topology can alleviate this problem by a 30° phase displacement angle.

Reference [85] studied asymmetrical machines, which are famous for their torque smoothness and steadiness. Fortunately, new methods have also been proposed to overcome torque ripple and fluctuation issues for symmetrical machines. For example, a high-frequency PWM was adopted by [86] to achieve a stable torque output. Moreover, Ref. [87] claimed that asymmetrical six-phase machines are capable of being fault-tolerant by implementing one neutral connection, rather than two.

Finally, there exists a study on dual-three-phase machines in [80], which stated that shifting the machine's coils 30° apart from each other will result in the mitigation of the fifth and seventh harmonic contents. Since there is no zero sequence component in this winding structure, it enables for easier control and efficient voltage utilisation [87].

The multiplication of phases can reduce the torque ripple and harmonic components in the machine's current waveform, which results in a more efficient system. Additionally, electrical power can be shared efficiently between each phase and provide much more tolerance against faults [88].

These machines can remain in operation even if one or two phases fail [89], and once torque ripple arises due to magnetic saturation, the torque density can be improved by injecting a third harmonic [90]. Dual-three-phase PMSMs achieve dual redundancy against faults with two inverter circuits [91]. Additionally, for multiphase structures, the extra switching leg provides additional redundancy [92].

However, there are some issues with multiphase machines, such as being unable to create an air-gap flux at some of the stator current harmonics [88]. All of these harmonics are limited by the stator resistance (R_s) and leakage inductance (L_s). Additionally, these harmonics can occur in the case of any voltage excitation due to a low-impedance current path, where the current flows with small resistance, regardless of whether it is normal current or fault current [93].

In terms of permanent magnet synchronous machines (PMSMs), it should be noted that back-EMF also contributes to current harmonics [91,92,94] and that the torque ripple becomes relatively larger as the amplitude of the harmonic current gets larger.

In [78], there is a comparison of three and six-phase permanent magnet machines. As inverter circuits exist, fifth and seventh harmonics are induced on the stator windings, potentially causing extra losses in multiphase machines.

Figure 10, produced based on the literature reviewed in Section 3, shows a comparison chart of traction motors in terms of efficiency, torque density, control complexity, maintenance cost and durability. It can be seen that there is no best option for every aspect, but an optimum one, multiphase PMSM, does exist. In light of the given advantages, such as smooth torque transition, torque density, control simplicity and fault-tolerant properties, these machines are great candidates for railway traction systems.

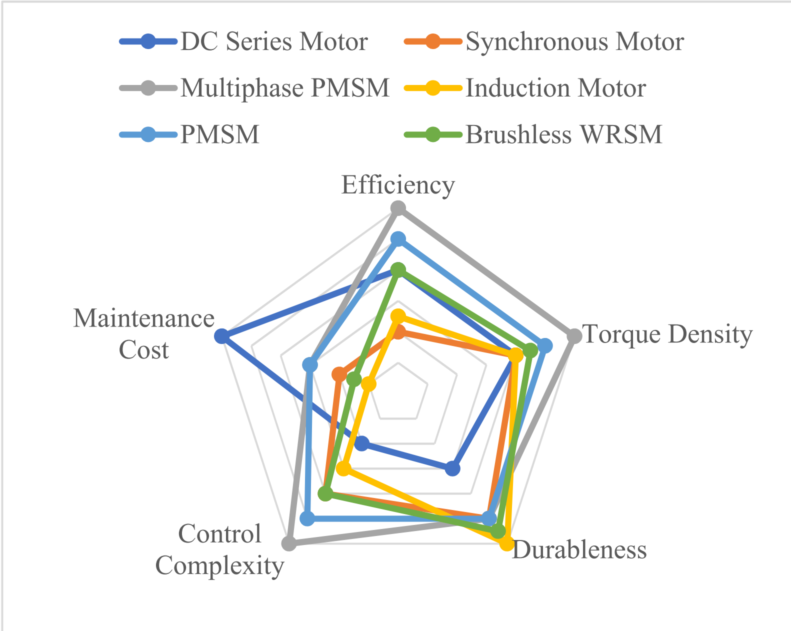

Figure 10. Spider web comparison chart of traction motors.

4. Power Converter Unit of Railway Applications with Wide Band Gap Devices

Power converter units have recently been extensively developed for railway applications. As explained for the hybrid traction drive system, inserting ESSs is one of the most popular topics, particularly for DC-powered railway systems [95]. Then, the regenerative inverter is a surrogate option for gaining excess energy through the AC grid. Additionally, different old methods were adopted to compensate for voltage drop/fluctuations, power factor correction and three-phase imbalances within a given time period, such as static VAR compensators, railway static power converters, frequency converters, etc. [95]. The most recent solutions address power electronics and switches to increase the efficiency of railway traction systems.

4.1. DC Motor Drives

Despite the fact that DC traction motor drives are practically obsolete, a summary of their capabilities is given here.

DC traction motors and drives were reviewed in [96] and are not popular nowadays because of the disadvantages of DC motors, such as the requirements for maintenance, efficiency, robustness and reliability. As such, a DC–DC chopper converter, a two-quadrant traction chopper, an AC/DC rectifier and a semi-controlled phase converter are employed as DC motor drives for railway applications.

4.2. AC Motor Drives

After the development of semiconductor switches, GTO thyristors became popular for AC motor drive circuits, and these motors have played an important role in railway traction systems so far. Traction drive systems for AC induction motors were reviewed in [97]. The main drives for AC motors, used for either induction or permanent magnet motors, are DC-fed current source inverters, DC-fed voltage source inverters and AC-fed voltage source inverters.

4.2.1. DC-Fed Current Source Inverters

Figure 11 shows how current source inverters (CSI) were utilised in electric vehicles and hybrid electric vehicles to overcome the shortcomings of voltage source inverters (VSI) [98]. They have fewer switches and a smaller dv/dt rate, as well as improved reliability in terms of excess current protection. As might be expected, the presence of large inductance restricts dynamic performance [99]. It should have a chopper circuit before the inverter to supply a constant current through the inverter. Having a DC chopper increases reliability in terms of the current defect and reduces power losses, thereby enabling a high starting torque [97].

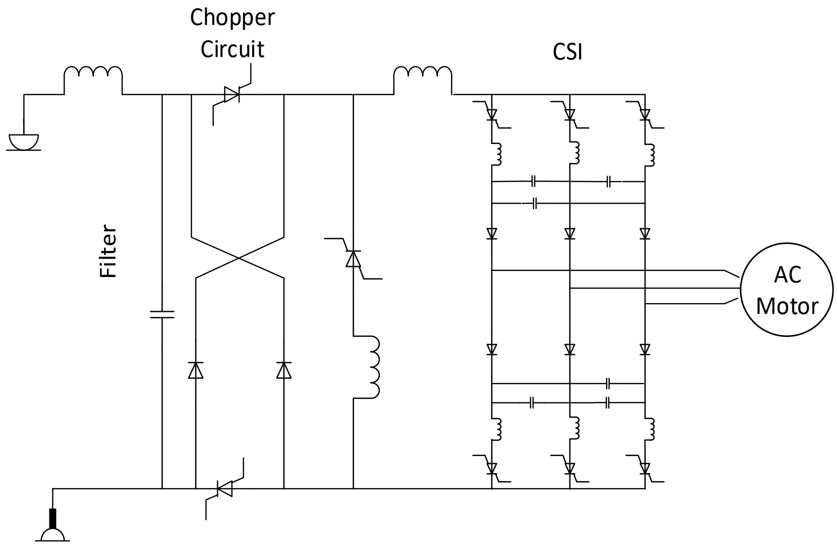

Figure 11. DC-fed CSI.

4.2.2. DC-Fed Voltage Source Inverter

Two-level and three-level voltage source inverters (VSI) are the most common types of inverters used in railway applications, and DC-fed VSIs have been fed from a DC source as shown in Figure 12. Due to its energy-saving features, regenerative braking is going to be essential for modern trains. Hence, recent development is centred around the compatibility of inverters with regenerative braking. In the literature, there are IGBT based, cost-effective, PV-supported reversible converters [100–102]. Additionally, the working characteristics of inverters need to be considered and were discussed in [103–105] in terms of voltage control techniques.

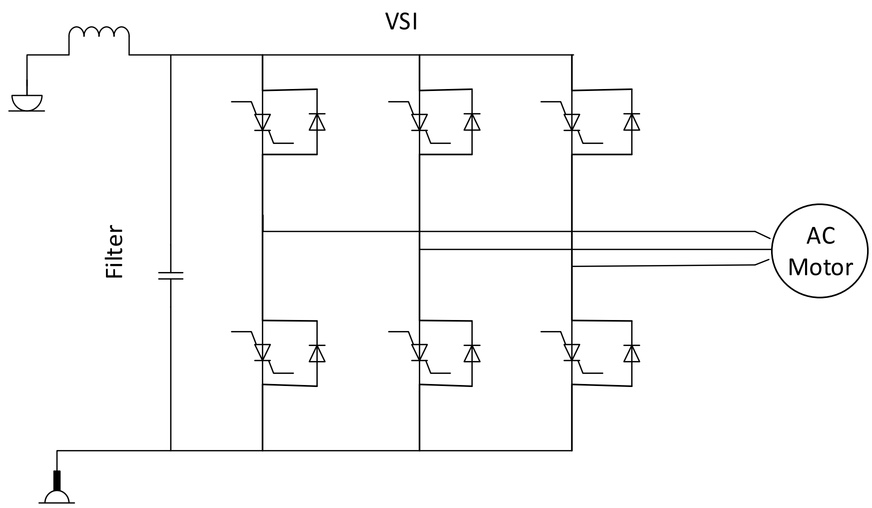

Figure 12. DC-fed VSI.

Furthermore, the requirement of a large capacitor for the filter is a disadvantage of DC railway power converter units. Therefore, PWM converters [106] and double converters [107] are employed to convert power from DC to AC systems, and [108] proposed a dual-winding isolated CUK converter that requires smaller capacitors and delivers a continuous current.

Two-level converters are most suitable for low-voltage applications (<1000 V AC RMS and <1500 DC) by utilising wide bandgap semiconductors, which offer higher efficiency with high power density [11]. On the other hand, multilevel converters provide lower switching losses and semiconductor stress with better power quality compared to two-level converters in medium voltage applications. Therefore, the comparison is based on two-level and three-level inverters.

A two-level converter generates $+V_{dc}$, $-V_{dc}$ and 0 at the output, either voltage or current. It has some restrictions in terms of frequency level that are implicitly affected by switching losses and semiconductor ratings in high-power applications [109]. However, three-level converters produce $+V_{dc}/2$, $-V_{dc}/2$ and 0 states, and have three types, namely diode-clamped, capacitor-clamped and cascaded inverters [97,109]. The main advantages of three-level converters are that they have lower DC components and a higher switching frequency that can be double that of the real value [109]. In addition, the voltage waveform became more sinusoidal with NPCs due to the fact that the rate of frequency could be four times that of the real frequency. With this contribution, the level of current ripples, torque pulsations and overall losses might be reduced [110].

Utilising fault-tolerant T-type NPCs provides fault-free operation due to having a greater degree of freedom for switching scenarios. Three-level T-NPCs also have outstanding harmonic performance and efficiency, small common-mode voltage and EMI, as well as high reliability [111]. In addition to T-NPC converters, D-NPC, two-level and three-level converters [112,113] can be considered fault-tolerant power-conditioning units. A brief comparison is given in Table 2 and [111].

Table 2. Performance comparison [111].

	Two-Level	D-NPC Three-Level	T-NPC Three-Level
IGBT Voltage	U_{DC}	$U_{DC}/2$	$U_{DC}/2$, U_{DC}
Harmonics	High	Low	Low
Loss (5–30 kHz)	Large	Middle	Small
EMI	Large	Small	Small
Fault-Tolerant Capability	Low	Middle	High

4.2.3. AC-Fed Voltage Source Inverter

AC fed VSIs are fed from DC, which is derived from the AC source, as visualised in Figure 13. It consists of an intermediate rectifier circuit. Diode clamped, fly-capacitor clamped, active neutral point clamped and multilevel converters have been investigated [114]. Most research has focused on the following issues: power quality, negative sequence current, harmonics and reactive power. For example, static VAR compensators [115], active power filters [116] and static synchronous compensators [117] were studied to mitigate the aforementioned issues. Additionally, ref. [118] provided a solution for power quality and, in particular, the neutral section.

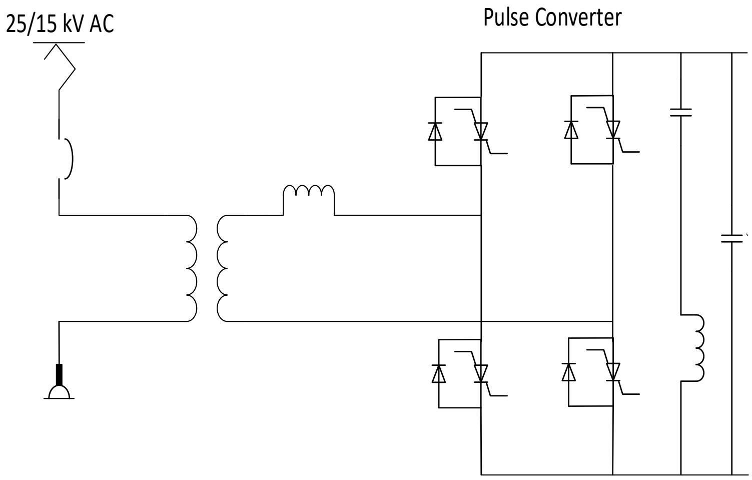

Figure 13. AC-fed VSI.

4.3. Recent Trend

Power converter units have been updated regarding the energy efficiency of the traction drive systems. Herewith, the use of energy storage units in traction drive systems has become a hot topic. The usual DC traction drive system includes a traction transformer and either a 6-pulse or 12-pulse uncontrolled rectifier, which was covered in [119]. Total harmonic distortion is the main disadvantage of this traction system. Therefore, Ref. [120] proposed adding a passive filter and [121] proposed a filter with a static var compensator. For the sake of power quality, a shunt active power filter is used to remove the harmonics in the [122,123] configuration given in Figure 14.

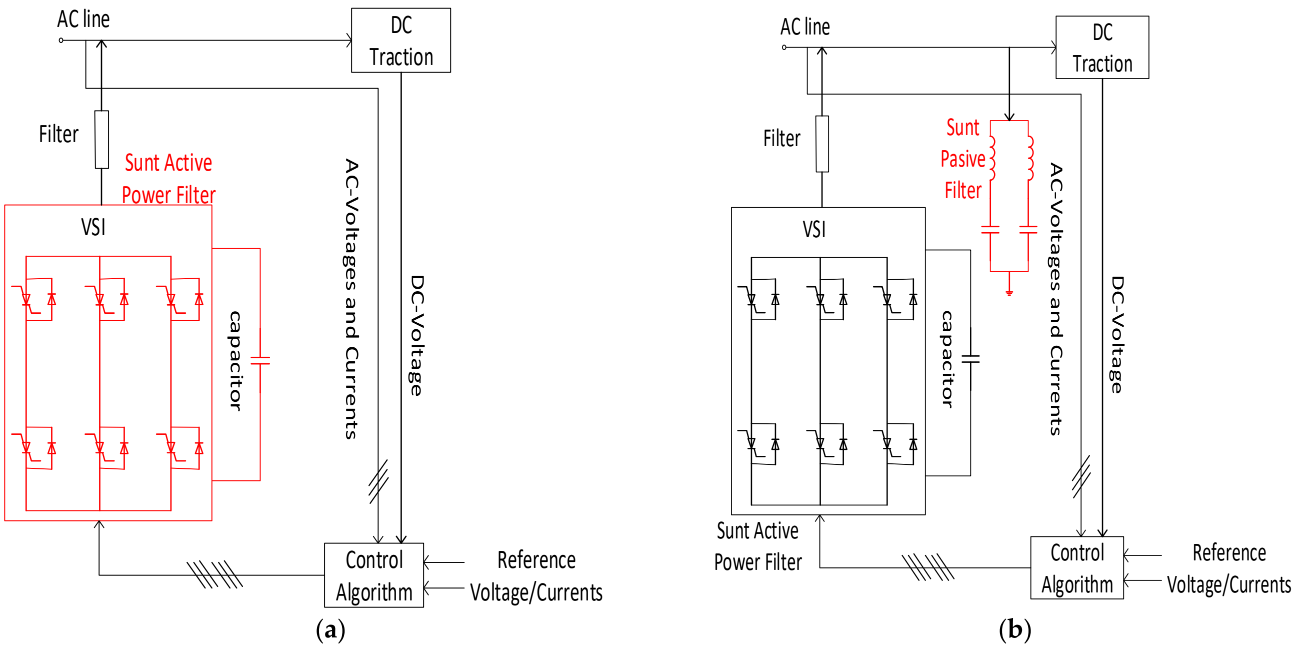

Figure 14. Shunt active power filter: (**a**) simplified model [122], (**b**) hybrid version [123].

Additionally, there exist some studies on reversible traction substations that increase the flexibility and receptivity of DC lines. For example, bidirectional reversible traction substations have been considered to improve power quality. Therefore, Siemens developed a commercial power converter unit called Sitras-TCI (thyristor line commutated inverter), as shown in Figure 15. It allows storing the braking energy at the medium voltage grid side, enabling energy transfer between the vehicles and reducing current ratings by half compared to the topology used in the forward rectifier.

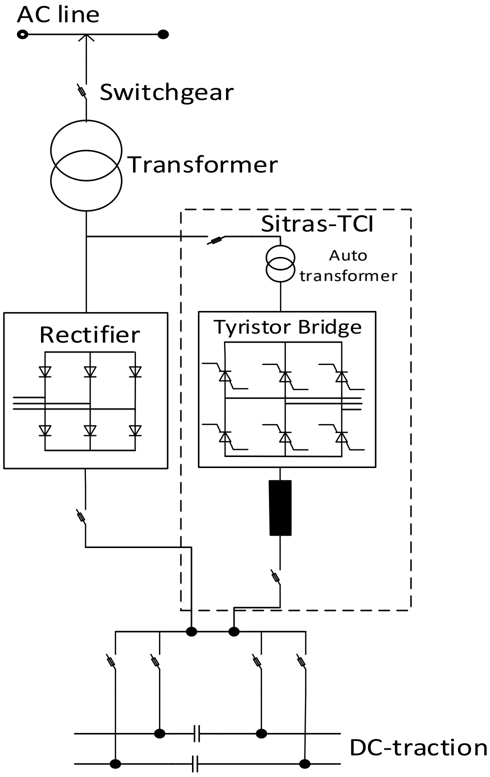

Figure 15. Siemens Sitras-TCI substation.

A traction company called INGETEAM commercialised the INGEBER system illustrated in Figure 16. The topology has an energy-recovery system (ERS) integrated between the secondary side of the transformer and the catenary line. An ERS includes an inverter, a chopper, a coupled inductor and a DC side connection. For the grid side, this configuration produces high-quality AC [124].

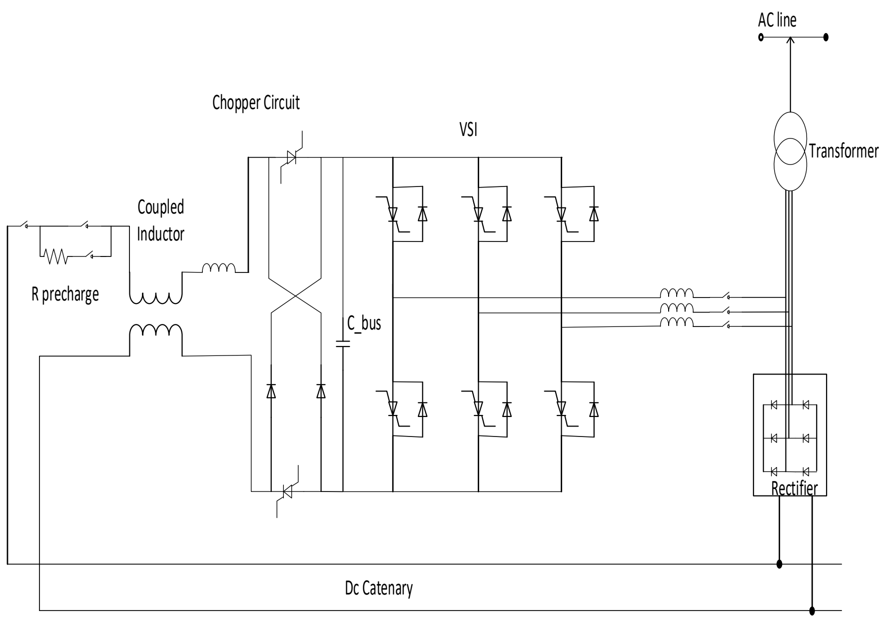

Figure 16. INGEBER configuration.

Alstom designed a converter that reduces harmonics and saves energy by paralleling a thyristor rectifier with an inverter and inserting it between the transformer and the railway network, as given in Figure 17. With this configuration, the main target is to increase the regenerative braking performance by over 99% [125].

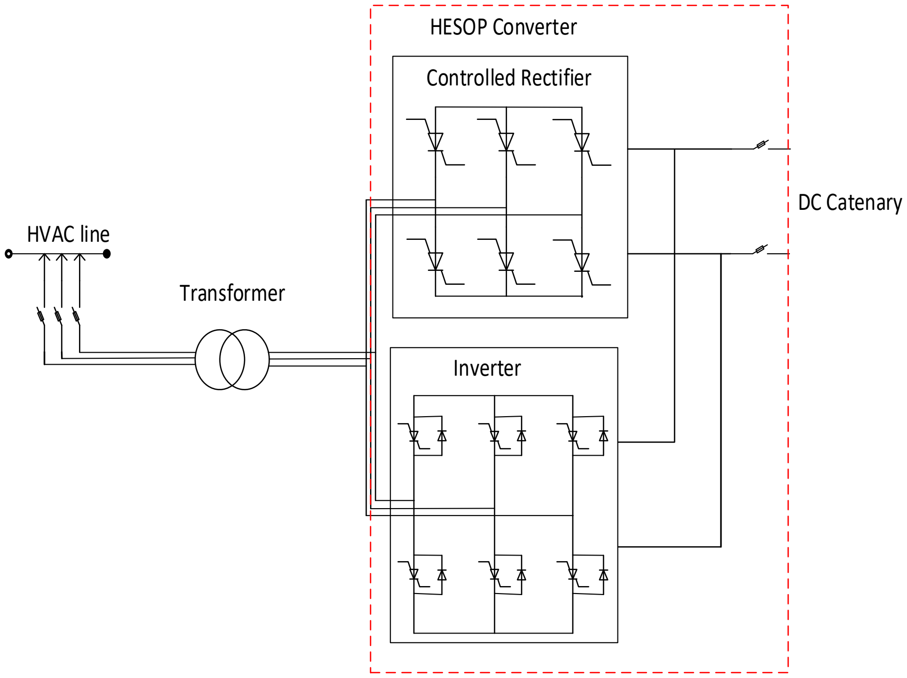

Figure 17. Harmonic and energy-saving optimizer (HESOP) converter [101].

On the other hand, HESOP is improved by the French railway company (SCNF) in Figure 18 to ameliorate the energy performance by reusing the braking energy. The control system of this substation schematic allows harmonic and short-circuit current reduction with voltage regulation [126]; additionally, it is used actively to transmit energy to the AC grid from the catenary directly.

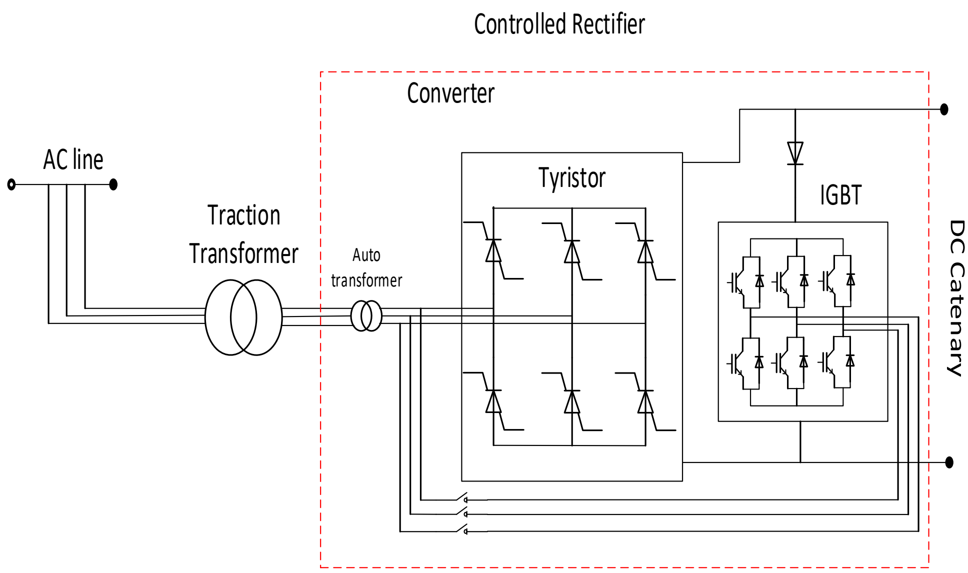

Figure 18. Improved HESOP converter by SNCF [126].

Then, Alstom proposed another HESOP configuration to combine the rectifier and the inverter shown in Figure 19. In this substation model, the converter works as a bidirectional for both rectification and inversion. It was employed on the London Underground as a trial, as illustrated in Figure 20. Therefore, it was connected separately to the substation, rather than paralleling with the rectifier or using it as a bi-directional converter.

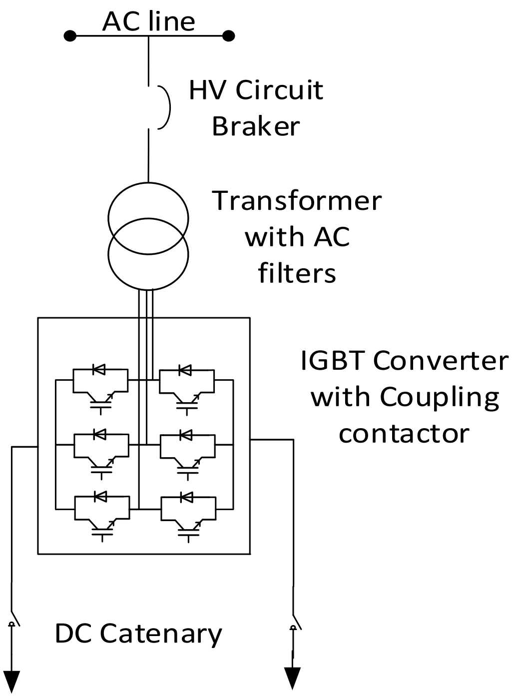

Figure 19. Updated HESOP Configuration [127].

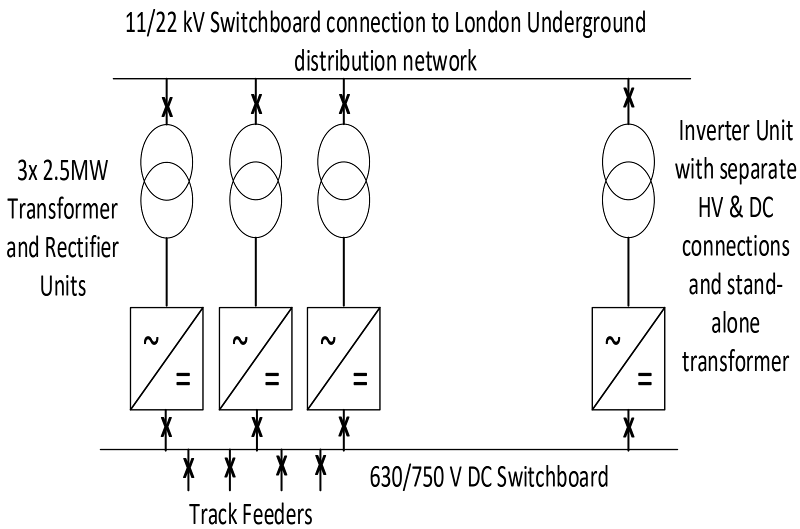

Figure 20. Upgraded version of the traction system of the London Underground [128].

4.4. Multi-Source Converters

Despite the fact that multisource converters were proposed and implemented for automobile applications, light railways should be mentioned as a potential future application.

Typically, electric vehicle power converter units use a DC link to connect the energy sources, traction inverter and the motor [126,128]. Even though the multisource concept reduces cost and control complexity, it decreases efficiency during light loads due to the utilisation of a constant DC-link voltage [129]. Recently, manufacturers have inserted a DC to DC boost converter between the DC source and DC link to overcome this issue for electric vehicle applications [128,130–132].

On the other hand, the purpose of multi-source converters is to connect independent supply sources, which might be DC sources, to the same AC output to reduce the conversion stage level. Without the use of an additional power converter, the multi-source inverter can drive a traction motor from varying DC voltages [129].

One topology has the converters being fed from two isolated DC sources [82]. The other configuration is powered by one DC supply to two inverters in a five-phase motor drive and enables the drive to have doubled output voltage as it connects each phase to an H bridge. Additionally, the concept design was given in [82], which consisted of four inverters, two sources and a common capacitor located between the coupled inverters. It is obvious that an extra capacitor is required for this topology, and a three-level output can be derived with this configuration. Technical details, such as the output current and converter performance, were discussed in [133,134].

The production of individual voltages from a few DC sources is targeted by a multi-source power converter and uses a single conversion stage. The output voltage is derived from distinct and independent input sources in a multi-source inverter as compared with a multilevel inverter that produces many output voltages from a fixed ratio of the shared DC input source [135].

A couple of multi-source converters were proposed in the literature, but some of them suffer from modularity. The others can only include two DC input sources and lack enough operation modes. However, the most important factor is modularity, which enables us to raise the number of DC sources, and that makes the system much more reliable during the breakdown of one or more sources [136]. For instance, the topology in [136] enabled an extensive number of DC sources, including fuel cells, battery packs and supercapacitors, to be employed in such a structure.

It can be clearly stated that the need for a DC/DC step-up converter is eliminated by using the multi-source inverter. The motor can be operated directly from energy storage units without boosting its voltage with a DC/DC step-up converter. Hence, the overall conversion efficiency is upgraded due to the disuse of the second boost converter in the topology given in [132].

Moreover, ref. [137] proposed two-input two-output converters that could control power flow between each source and load. These converters are then interfaced with a multilevel inverter. The outputs of the constructed converter are fed as inputs to the multilevel inverter. This proposed converter uses just one inductor, and the converter can be employed for transferring energy between different energy resources such as photovoltaic (PV), fuel cells and energy storage systems, such as batteries and supercapacitors [137].

4.5. Impact of Wide-Band-Gap Devices

The use of insulated gate bipolar transistor (IGBT) was deemed appropriate in vehicular applications, because the high switching frequency and low voltage are key parameters for the converter; therefore, owing to the lower cost and higher performance of the IGBT devices, they are the best choice for the main switches [138]. On the other hand, the newest Wide-Band-Gap (WBG) semiconductors, such as Gallium Nitride (GaN) and Silicon Carbide (SiC), offer better switching performance.

The SiC power converter unit was first introduced by Odakyu Electric Railways for a 1.5 kV DC traction inverter, which was adequate to drive four 180 kW induction motors [139]. The volume of the power converter unit was reduced by 80% compared to the traditional 4.5 kV GTO inverter [139]. A 3.3 kV SiC MOSFET is employed on Series N700S Shinkansen electric multiple units to reduce the mass of the train, and it drives four 300 kW six-pole induction motors. Ultimately, the traction power converter unit occupies 30% less space compared to the traditional IGBT converter [140]. Mitsubishi launched a 140 kVA, 600 Vdc SiC commercial product in 2013 for the auxiliary power supply system of the Tokyo Metro. It reduces power loss by up to 30% and occupies 20% less space with 15% less weight and increased regenerative energy by 51%, while it was 22.7% for the Si-based module [141]. Additionally, Alstom implemented a 1.2 kV/100 A SiC device in Line 3 of the Metro Milan for charging energy storage units and auxiliary systems [142].

Additionally, Toshiba's European branch introduced a 1.7 kV/1.2 kA Injection-Enhanced Gate Transistor (IEGT), which includes SiC and a fast recovery diode for the propulsion converter [143]. Mitsubishi integrated and implemented a 3.3 kV full SiC module for a 1.5 kV DC traction inverter application that consisted of four 190 kW traction motors. By doing this, the volume and switching loss of the converter unit were decreased by 65% in size, 30% in weight and 55% in switching loss, respectively [144].

However, there are some technical challenges to the implementation of SiC power semiconductors in high-power applications. One of them is the design difficulty of parasitic inductance and the value of inductance itself, which were addressed in [145]. It is known that high voltage and current ratings, which are typically >1.7 kV and >500 A, of semiconductor modules are desired for railway applications [146]. A 3.3 kV/1500 A all-SiC traction inverter was developed with 55% fewer switching losses [147] and a 3.3 kV/500 A all-SiC module was recently designed for railway traction applications [146]. Furthermore, a 1.7 kV/1.6 kA hybrid SiC, which is utilised by Si IGBT and assisted by Schottky Barrier Diode (SBD), was proposed to decrease the design complexity [148].

The deterioration of gate oxide, which is a material degraded because of the electric field, is more critical for full SiC. Since it can affect the reliability and quality control of the module [149], due to the fast switching feature of WBG devices, the gate driver needs to be designed carefully to keep the performance of the module high. Therefore, signal isolators [150], integrated circuits of gate drivers [151], thermal capability [152] of the module and the switching transients [153] of semiconductors have been redesigned intelligently to achieve the best performance. Additionally, the filtering of EMI is becoming harder with high frequency. Some solutions have been proposed to find the optimum size and value of filters [154] and eliminate coupling effects [155] on the component.

The effects of dead time on modulation and voltage/current detection are particular challenges for these devices in terms of control. Adaptive dead-time adjustment was used in [156] to meet the desired efficiency and reliability balance. The quality of power is reduced at current zero-crossing due to the high switching rate. Although this causes voltage loss and harmonic distortion, ref. [157] regulated this by duty cycle, refs. [158,159] a proposed compensation of modulation and [160–163] adjusted the feedback control to mitigate this issue.

The transition to WBG devices will increase and be more efficient with the proposed remedies in railway applications.

5. Conclusions

An extensive review of railway traction systems and their requirements is given in this article. First, the efficiency of the traction drive system and traction motor designs was investigated, followed by a detailed discussion of the power converter and power semiconductors using various topologies.

Most light railway networks are electrified within urban areas all around the world. However, there are still unelectrified and diesel-propelled railways. Therefore, the superiority of electric and hybrid electric traction against non-electrified systems is revealed, and different diesel–electric configurations are displayed.

Furthermore, two major flaws in contemporary railway systems have prompted stakeholders to examine fuel cell-powered rail rolling stock. One of them is the demand for significant investment in the construction of electric infrastructure alongside railroad tracks, despite the fact that electrification reduces carbon emissions. The other is that, despite the lack of a catenary, diesel propulsion emits the same amount of pollution as ICE-equipped vehicles on the road. As a result, for the decarbonization of vehicular applications', fuel cell battery-powered rolling stock and hybrid autonomous systems come to mind. They are both zero-emission and low-cost to install.

Afterwards, three-phase and multiphase PMSM traction motors were analysed, and the prodigiousness of PMSMs was underpinned by successfully implemented applications.

The main benefits of a multiphase machine structure are the increased torque per unit volume and reduced torque pulsations in the motor. For example, typical light railway systems have four, six or eight motors that, depending on their ratings, take up a lot of room onboard. When multiphase machines with the same ratings are compared to three-phase machines with the same ratings, the multiphase motor power is unavoidably denser. As a result, the traction motors take up less room in the car. Furthermore, torque pulsation plays a vital role in motor vibration that could be reduced with multiphase machine construction.

Multi-phase machines, as previously stated, have a higher torque density than their three-phase counterparts. Therefore, adopting multi-three-phase machines could reduce the number of motors. However, the adhesion issue also arises in this instance. The adhesion force is particularly significant for high-speed and high-power freight trains. As a consequence, there are two possibilities for railway traction drive systems: either the use of a medium-voltage converter with concentrated (fewer motors) motors or a low-voltage converter with the same number of motors.

Higher efficiency is achieved by using medium voltage and a concentrated motor converter architecture. Additionally, because a medium-level DC connection voltage is necessary, a boost converter should be employed. The number of motors will remain the same as before, but a low-voltage power converter will be used. There is no need to boost the converter in this situation, and the power element ratings are much lower, resulting in significantly lower power and switching losses. The power conditioning unit will be less expensive and more reliable than the medium-voltage topology.

Then, a more in-depth investigation of the traction power converter units was given with a brief introduction to multisource converters and WBG power semiconductor technologies. Multisource power converter units are offered for the multiphase structure to increase the reliability of the system. In addition, a few proposed structures support these converter topologies to allow fault-tolerant functioning.

Finally, WBG devices were analysed, and possible obstacles were inspected to make them more efficient for implementing railway applications. The thermal durability and packaging materials have a key role in the purpose of efficiency.

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