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Opportunities and Challenges of Power Electronics Systems in Future Railway Electrification

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Abstract— **With the continuous expansion of the railway power systems, the integration of high speed locomotives and the need to increase the overhead catenary line power capacity, the main shortcomings of the conventional railway feeding system are becoming more evident. In order to overcome these drawbacks and to contribute to the technological evolution with innovative and electrically more efficient systems, several solutions have been proposed and implemented. In this context, this paper briefly presents a study of different railway power systems, highlighting emerging concepts, such as regenerative braking, energy storage systems, the inclusion of renewable energy sources, bidirectional power flow and wireless power transfer. Some of these concepts can be implemented in short to medium term, or in the long term. Following these concepts, an overview of the power electronics challenges for the implementation of these emerging concepts is presented and discussed.**

Keywords— Electrical Railway Power Supply Systems, Energy Storage System, Power Electronics, Regenerative Braking, Renewable Energy.

I. INTRODUCTION

The railway system has maintained its long-standing position as one of the main pillars for passenger and freight transport. This leads to the fact that the railway system may add a distinct footprint for the economy of each country. All these factors have encouraged investment in the railway sector. In fact, the conventional railway system already accounts for almost one-sixth of the long-distance journeys between cities [1]. Nowadays, the high-speed railway system is increasingly attracting interest as a safe, economical and environmentally-friendly substitute for short-haul intercontinental flights. However, and in order to reduce congestion, pollution and travel time in metropolitan areas, the subway is a more interesting service for this requirement. On the other hand, regarding freight transport, rail solutions are equipped to transport large quantities of goods. Overall, the electric railway systems are the most efficient and least CO_2 emitting comparing to other transportation modes [1].

The potential of the railway system to meet the forthcoming mobility demand of the future is enormous. This feature is reflected in China's strong bet on high-speed railway systems, moving from a nonexistent infrastructure in 2008 to one with a total length of 41 000 km within 10 years. Worldwide speaking, the metropolitan railway line has a length of 53 000 km and the high-speed railway line has a length of 68 000 km, representing an annual growth of 11 % per year from 2000 to 2016. Despite the truth that people use 5 times more electrified trains than the non-electrified ones, it is important to highlight that almost only 1/3 of the railway systems in the world are electrified [1]. One of the main booster of the railway system in the 21st century is the financial initiatives of several world nations. For instance, Shift2Rail presents itself as a European organization committed to contributing to technological development in this area, as well as reducing rail life cycle cost by up to 50 %, doubling rail capacity and increasing reliability by up to 50 % [2]. In order to accomplish this objective, it is necessary to develop innovative solutions for railway systems, where power electronics play an important role. To study the opportunities and challenges of power electronics in railway systems, special importance was given to the new concepts of emerging locomotives. Table 1 shows the 11 fastest locomotives to be commercialized in the near future.

This paper is structured to give an insight into the challenges and trends for the railway power system. The second Section presents the different emerging concepts that can be integrated into the railway power system. The third Section addresses the power electronics challenges in order to successfully implement the emerging concepts. Finally, Section IV presents the main conclusions of the paper.

TABLE I. FUTURE TRENDS ON HIGH-SPEED LOCOMOTIVES

	Locomotive	Start Service	Maximum Speed	Power (MW)
11	CRH3X	2020	350 km/h	2 (per traction unit)
10	Oaris	2015	350 km/h	5.28-10.56
9	Avelia Liberty	2021	350 km/h	N.A.
8	Avelia horizon	2023	350 km/h	8
7	Velaro novo	2023	360 km/h	8
6	Talgo Avril	2020	365 km/h	8.8-10
5	Alfa-x e956 Shinkansen	2030	400 km/h	N.A.
4	Hemu-430x	2015 (ktx-III version)	430 km/h	8.2
3	CRRC Maglev	2021	600 km/h	24
2	L0 series Maglev	2027	603 km/h	N.A.
1	Hyperloop	2030	1200 km/h	21

N.A. Not Available

II. THE FUTURE OF RAILWAY POWER SYSTEM

The development of electronics has enabled the introduction of new systems in everyday life. One of the revolutions of the last years is the real-time sensing of the systems, where the railway system was not an exception. With sensing, it is possible to determine and control the geographical location of each locomotive as well as to predict the energy consumptions in order to create a more efficient feeding system. The European Rail Traffic Management System (ERTMS) has become a widely used solution, becoming world dominant in sensing and controlling the railway system. The ERTMS was a project executed by the European Railway Agency (ERA). This system enables the prediction and adaptability of the system to increase catenary capacity by 40%, reduce power grid dependency by 15%, reduce carbon emissions, increase safety, among others characteristics [1].

One of the most important topics in power electronics research is the development of solutions that allow the interfacing with alternative propulsion technologies, such as fuel cells or hybrid systems, essentially for non-electrified sections, in order to reduce the cost associated with installing and expanding the electrical supply system [3]–[6]. They also argue for the installation of Energy Storage System (ESS), both internal and external to the locomotive, for a better distribution of energy according to their needs, thereby enabling the recovery of energy from regenerative braking [6]–[9]. However, the integration of renewable energy sources and concepts such as smart grids would not only enable local energy generation more efficiently but also increase the flexibility in the supply and exchange of electricity. Additionally, with the integration of local energy sources, it would be possible to increase energy efficiency as well as to reduce the overload on the power grid and thus enabling the integration of more or larger electric locomotives in the same railway system [7]. Some of the future railway trends are presented in Figure 1, being described detailed in the following topics.

A. Cooperative Strategy

As the mobility demand increases at a faster pace than technological developments and consequent market integration, rail sensing helps to manage locomotive distance and travel time, providing a more efficient railway system and improving the experience of the passenger. This offers the possibility to develop cooperative strategies easily integrated.

One of the most commonly used cooperative strategies is to combine the time between the arrival of one train and the start of another. This makes the possibility to directly take advantage of regenerative braking energy to assist the running of another train, represented in Figure 1 (c). Nevertheless, and with the sensing of the entire railway, it would be possible to implement control algorithms capable of detecting the best moments of acceleration and deceleration of the locomotives in order to optimize the energy consumed. In [8] two different driving strategies for the same trip are presented, showing different consumption and regenerative braking curves.

Another very interesting short-term cooperative strategy is the bidirectional energy flow between adjacent traction substations. This type of solution would increase energy efficiency as well as reducing the local power consumption in the substation. In other words, this solution enables higher power capacity as well as the insertion of more locomotives in the overhead catenary line. In some cases, this enables a decrease in the sizing of certain elements such as transformers, converters and transmission lines [8]. Hitachi has been exploring this concept where the initial results have exceeded the expectations. In [10] a system called sectioning post - Railway Power Conditioner (sp-RPC) was installed in a Neutral Section (NS) located between two traction substations that allowed the direct use of energy from regenerative braking, as is represented in Figure 1 (f). The major challenges of this strategy lie essentially in the sensing and consequent management of the generated data. Sensing is a key step for developing an autonomous system that can predict and detect faults. However, big data generation needs to be managed and transmitted over long distances

B. Energy Storage System

One of the strong research trends is the inclusion of an ESS close to the local consumption, making the railway system more independent from the power grid. In some cases, the ESS may be directly included inside the locomotive. Therefore, a feasibility study of different energy storage technologies (presented in Table I) is required. Depending on the design requirements, there are more recommended technologies for mobile and other stationary applications. In [7], [11] is presented with more detail a comparison of different ESS. In [12] an experimental test is presented of the installation of an off-board inertia flywheel in a substation in Madrid, Spain, stating that the combination of different ESS technologies could provide a more efficient and reliable system. With the advancement of technology, it was possible to create solutions based on very compact and desirable implemented on-board flywheels, as used in Rotterdam [13]. In charging systems for such applications using electrochemical batteries, there is a strong concern in the development of power electronics to enable rapid charging. To do this, many systems use an intermediate stage consisting of supercapacitors that provide a better transient response, and batteries are responsible for storing the largest share of energy [6]. In this context, it is possible to manage the charging method imposed on the batteries, allowing them to preserve their lifetime. Regarding the fuel cells, different results on hydrogen consumption, efficiency and battery charging state intervals are shown in [3] in locomotives with different rail uses. The introduction of ESS in the railway system makes it possible to improve service interruptability even in the event of a power failure by providing both on-board and off-board power to the locomotive. The on-board and off-board configurations are presented in more detail below.

TABLE II. ESS TECHNOLOGIES (BASED ON [7], [11], [14]).

	Fuel Cell	**Batteries**	**Flywheel**	**Supercapacitor**
Energy Density	Very High	High	Low	Medium
Power	Medium	Low	High	High
Fast Charging	Yes	No	Yes	Yes
Lifetime	Medium	Low	High	High
Cost	High	Medium	High	Medium

1) On-Board Energy Storage System

By integrating an ESS on-board of the locomotive, it is possible to create a more independent means of transport than the conventional stationary feeding system, which allows the creation of catenary-free zones in some locations, as presented in the labels (i), (j) and (k) in Figure 1. This fact is especially favored in historical areas as well as in areas with greater difficulty of construction as in bridges and tunnels [6], [11], [15]. The essence of this feature is the fact that the locomotive has an internal power source allowing uninterrupted service in the event of power failure or when the locomotive is immobilized in a NS supply zone. In addition, taking into account the cost of implementing the power system and its extension along the railway, the most commonly used lines have priority in rail electrification. As a consequence, there are a number of non-electrified railway sections where on-board ESS can be a very viable solution [16]. Additionally, this configuration allows for greater efficiency in the event of regenerative braking, as there are no energy losses along the power transmission lines [6]. Experimental results of the integration of an ESS in Seville metro, Spain, are presented in [17], showing an overall efficiency of 84.4 %. Nevertheless, with this configuration, each locomotive within a railway line can be considered as a microgrid, generating and consuming energy, being the surplus transmitted by the overhead contact line to an adjacent train for energy storage application or directly to aid in locomotion or can be injected into the power grid. From a technical point of view, on-board ESS facilitates the implementation of control algorithms with virtually instant access being variables to be controlled. In contrast, one of the major disadvantages of this configuration is its difficult adaptability to the existing conventional systems.

For the power supply of on-board systems, there are different solutions: in [7] and [15] are presented some examples of a fast loading incorporated in the ground and placed in the middle of the railway track, where the ESS is charging continuously along the rail section. In [6] is presented other type of this system,

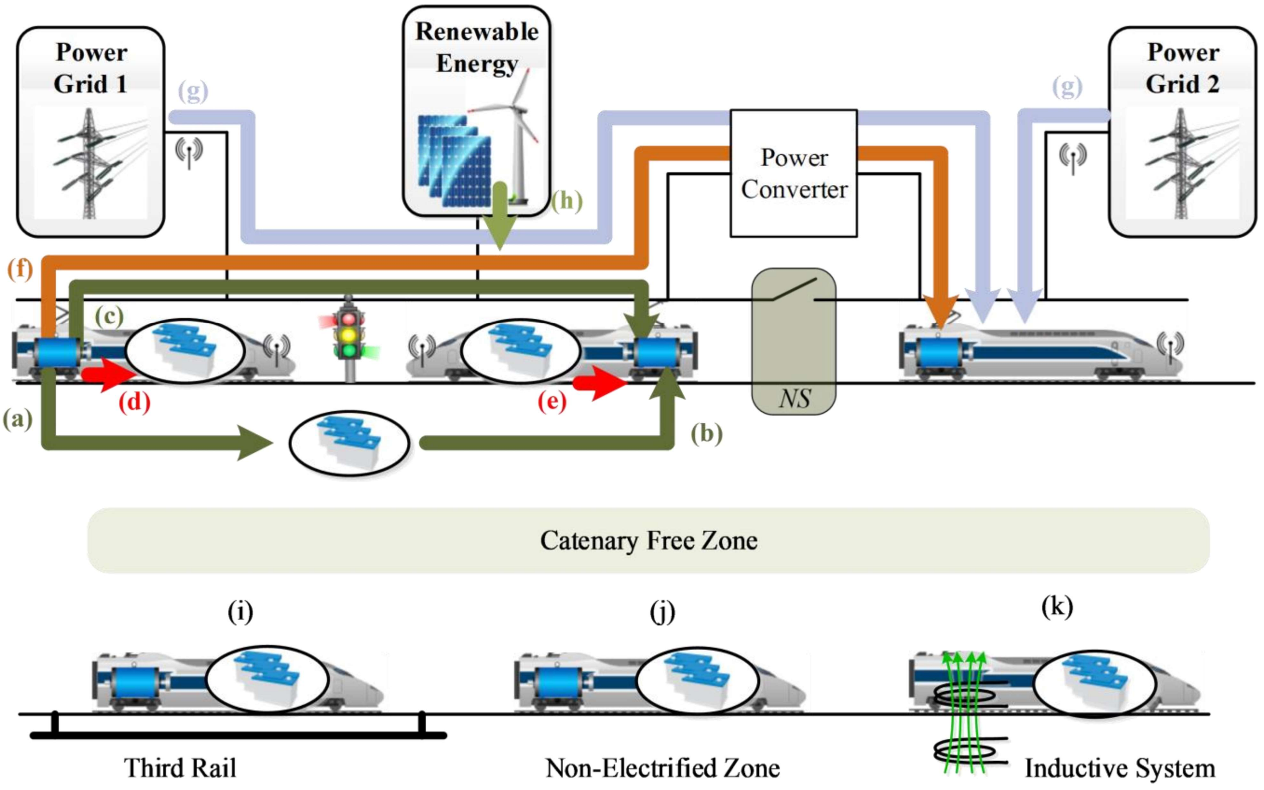


Figure 1 – Representation of some future operation mode trends: (a) Regenerative braking energy stored in an off-board ESS; (b) Energy stored in an off-board ESS used to assist the running of a locomotive; (c) Regenerative braking energy directly used to assist the running of another locomotive on the same catenary; (d) Regenerative braking energy stored in an on-board ESS; (e) Energy stored in an on-board ESS used to assist the running of a locomotive; (f) Regenerative braking energy directly used to assist the running of another locomotive in adjacent catenary; (g) Different power grids are used to balance power in the catenaries; (h) Renewable energy interface; (i) Third rail in overhead catenary-free zones; (j) Use of on-board power sources for running in catenary-free zones; (k) Wireless power transfer systems.

where the feed cage is made laterally on the third rail (as represented in Figure 1 (i)). A cheaper and more adaptable solution is presented in [14], incorporating small catenaries only in the railway stations, being the stored energy used for the locomotion of the locomotive until the next station, as represented in Figure 1 (j), initiating a new ESS charging process. A more innovative solution is presented in [15] where a wireless power transfer system is used to charge the ESS, identifying the different existing projects as well as the biggest advantages and disadvantages of each solution.

The biggest challenges regarding the implementation of such technology lie in creating an ESS with a high specific energy density: high amount of stored energy with lightweight. Another challenge lies in adapting existing locomotives and vehicles to such an ESS. An example of an adaptation of a locomotive with the creation of a lower contact for power supply is presented in [18]. However, projects to adapt an on-board ESS are normally rare due to the costs and the inherent difficulty to adapt the existing structure.

The *Siemens cityjet eco* project consisted of the adaptation of a conventional locomotive, developing a functional prototype with a 500 kWh battery ESS that provides a range of 80 km and achieves a maximum power of 1.3 MW and a top speed of 140 km/h. The main objective is to obtain knowledge for the serial production of on-board battery locomotives. Another project is the *Bombardier talent 3* that aims to be completed by 2020, six locomotives with on-board batteries that allow to reach speeds of 160 km/h and autonomies up to 100 km in catenary-free zones.

2) *Off-Board Energy Storage System*

The off-board ESS can be used in conjunction with renewable energy sources to store energy at peak production times. Additionally, it can also be used to store energy from regenerative braking, as presented in Figure 1 (a). However, all stored energy can be used not only to help the locomotives movement, as represented in Figure 1 (b) but can also be used to power the inherent railway system, such as passenger railway stations and car parks [19]. With the inclusion of ESS in strategically chosen locations along the railway it would be possible to impose a more efficient and independent railway system with energy sources closer to the consumption places.

As it is a fixed solution, specific energy density is not a priority, thus having a smaller initial investment [20]. Additionally, this solution is easily adaptable to conventional feeding systems and is very attractive for nowadays applications as well as in the near future, considering the sufficient fleet of locomotives without the possibility of internally including an ESS. An example of this adaptability is presented in [21], where *Hitachi* Branch, East Japan Railway Company, has been implementing ESS between traction substations to take advantage of regenerative braking. One of the conclusions obtained was that in metropolitan stations, where the flow of locomotives is less than 5 minutes, the energy from regenerative braking is directly used by adjacent locomotives at start-up. The opposite scenario is in stations outside the metropolitan area, where trains flow is over 10 minutes, the total energy from regenerative braking does not justify the investment of an ESS. In order to take advantage of ESS, the correct location of installation is required, and a station where the flow of locomotives is on average 7 minutes is recommended. An example is the *Ushiku* station where it is estimated (based on the first 8 months of operation) savings of 2500 MWh/year [21].

The biggest challenges of this system lies in implementing control algorithms that can detect regenerative braking from a specific locomotive hundreds of meters or tens of kilometers away. The control system should orientate the energy resulting from the regenerative braking to flow near the ESS. An example of this concern is the migration of the GSM-R system to the LTE-R, enabling communication up to 12 km, at 50 Mbps of downlink and 10 Mbps of uplink data rate, with a success rate of over 99.9% for speeds up to 500 km/h [22].

C. *Renewable Energies*

As electric energy, is represented in Figure 1 (h), is indispensable for the electrification of the railway system, the inclusion of energy sources, namely renewable, near the places of consumption has been arousing a special interest in the scientific community. Initially, the major focus of integrating renewable energy sources was to feed power to the railway stations rather than the catenary. Thus, all renewable energy production would be for direct consumption, with the surplus stored in the ESS for later usage [23]. In [19] is presented a study based on computational simulations of the conjugation of various renewable energy sources with the regenerative braking to charge the electric vehicles that are parked in the substation neighborhoods. This conjugation of different energy sources looks very interesting considering the varied energy production of the solar photovoltaic (PV) installation throughout the day as well as throughout the year.

Although these concepts are quite commonplace today in lower power applications, renewable energy sources have not triggered a major investment focus for rail power. Considering the length of the railway lines, and the vast majority in constant sun exposure, at first glance it would be very attractive to install solar PV panels along de railroads. However, the inherent logistical problems in such fragile installations can be questioned. The fact is that there are already studies for the integration of this type of installation in Hyperloop, with different types of solar PV panels configuration for a better solar maximization. The results of these studies are presented in [24], whether the priority is to maximize energy production or to minimize the costs.

As a conclusion, the biggest challenge for the integration between renewable energy sources and the railway power system is the implementation of power electronics solutions. Power electronics converters have to be able to draw the maximum possible power over time from intermittent power sources. Nevertheless, and taking into consideration an example of a typical value of 200 W_p solar PV module with an area of 1.5 m^2, it would take 50 000 PV modules and an area of at least 75 000 m^2 to generate equivalent power of 10 MW_p solar PV installation, raising some logistical questions regarding the large area of the installation. In addition, this area value assumes that all photovoltaic solar modules are close together, with no space between them; however, it should be noted that usually, they need some inclination to maximize sun exposure, giving shades to the solar PV modules behind. Thus, it is likely that integrating solar photovoltaic installations will be more suited to lower the energy demand in smaller railway systems or in railway stations to feed lower power loads.

D. *Hybrid Power System*

Despite constant railway electrification, there are still several non-electrified extension zones due to the types of locomotives and the impossibility of extending the power line. In this context, a hybrid system presents itself as one of the most viable solutions. This system can combine the autonomy of a diesel engine with the efficiency, higher starting torque and the silence of electric motors. In fact, low noise is one of the necessary requirements in certain areas and/or periods of the day. As a consequence of this junction, the diesel engine may be smaller, reducing CO_2 emissions [6]. In addition, the electrical system will cover the torque gaps of the diesel engine, being the diesel engine responsible for providing average power and the electrical system responsible for providing power variations. This way, it is possible not only to improve efficiency but also to make the travel more comfortable for passengers [6].

E. *Wireless Power Transfer*

Despite being a concept characterized by low energy efficiency, wireless power transfer solutions, as is featured in Figure 1 (k), with efficiencies more than 80 % and 1 MW of power already exist [25]. Additionally, the low efficiency of wireless energy transfer is identified by the imperfect alignment of the inductive winding present in the power source with the inductive winding present in the load. However, in a railway system, this problem can be minimized to only one axle, since the locomotive maintains a fixed alignment both in height and width with the railway lines, varying only its longitudinal position.

From a more technical point of view, it is possible to identify resonant LC converters that combine inductors (L) and capacitors (C). These converters are characterized by their high volume/weight and short lifetime. Additionally, and in order to concentrate the magnetic field, ferromagnetic cores are generally placed, inflating the cost of installation as well as raises the question of installation feasibility along the public rails. Furthermore, any metal body (locomotives and train wagons) may affect the magnetic field and consequently disturb the previously considered electric model.

F. *Magnetic Levitation*

Another innovative concept is the electromagnetic levitation, using permanent magnets to levitate and propel the train wagons. Since there is no need for the rail wheels, this solution has lower friction which enables higher speeds and lower maintenance [26]. In this concept, it is possible to highlight two main projects that use the Magnetic Levitation: *Hyperloop* and *Maglev*. In [26], a detailed description of these two technologies is presented.

Despite the new concept, this technology has been struggling to enter the market decades ago. One of the main factors for this system is the long-term contracts for the exploration, manufacture, and maintenance of traditional locomotives and railways. At this point, it is possible to identify another factor with the interoperability of the service. These innovative, high-speed systems can only be effective when completely independent of slower and conventional systems. In addition, rail transport with totally different speeds at the same rail line raises safety concerns [27].

G. *Others Emerging Concepts*

One of the major concerns in railway systems lies in the constant power imbalance in adjacent overhead lines. In order to allow a greater flow of locomotives, it is necessary to increase the capacity of overhead contact lines without overloading them. Thus, one of the trends lies in the implementation of solutions capable of balancing the power in the overhead contact lines in order to allow the integration of more and larger locomotives in the railway system and/or to reduce the over dimensioning of the power transformers and the cable section. With this concept, as is represented in Figure 1 (g), it would be possible to make the railway system more efficient and less expensive [8].

III. POWER ELETRONICS SOLUTIONS FOR RAILWAY APPLICATIONS

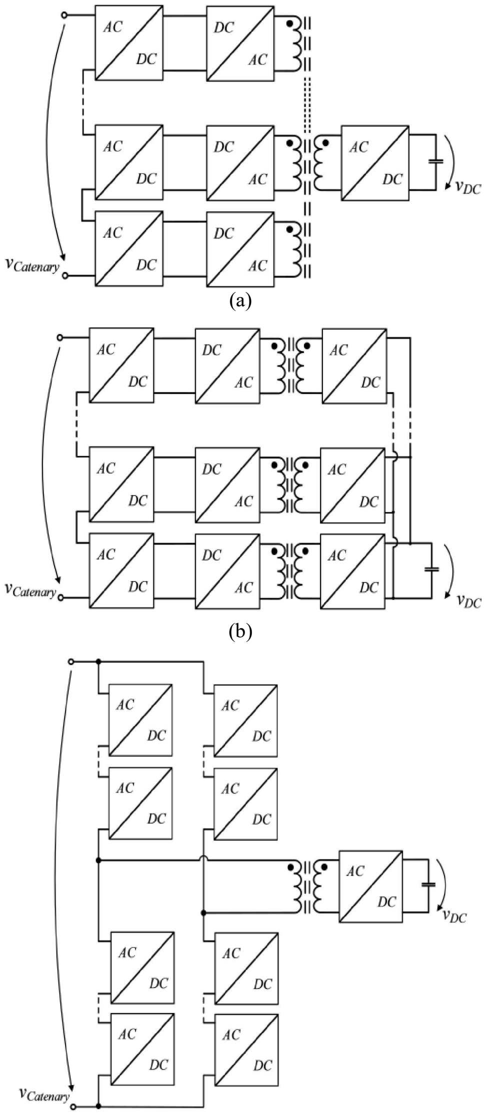
Looking at the railway system, there are systems to be supplied with DC power and others with AC power, with different voltage levels and frequency values. Using the 27.5 kV and 50 Hz railway system as an example, it uses power transformers to interface the 220 kV of the distribution power grid line with the 27.5 kV on the catenary. Scott and V/V transformer topologies are the most common in this type of applications [28]. However, in such configurations, it is necessary to create NS between catenaries fed by different power substations. Such requirements make impossible the bidirectional energy flow between substations in order to balance the power in the catenary. Additionally, despite being a simple and robust approach, NS makes it difficult to integrate of new concepts such as renewable energy or regenerative braking.

In order to change the conventional railway paradigm, creating a decentralized and more efficient system, it is necessary to develop power electronics solutions, both in terms of topologies and control algorithms, which allow the introduction of new concepts and features, such as, renewable energy sources, regenerative braking and the ESS. However, and due to the low voltages supported by the power semiconductors and the high voltages in the railway system, the implementation approach needs to be changed using for instance Modular Multilevel Converter (MMC). In Figure 2 are presented the most used configurations for traction [29].

The research field of MMC is quite recent and fertile and is expandable to other high-power applications such as wind power. In Figure 2, are presented different power converter configurations explored by different railway equipment manufacturers, being presented in [29] in more details. Over the last years, a dramatic change has taken place toward modular topologies, in which cascade-connected two-level converters behave as controllable voltage sources. In this context, Figure 3 shows the most common converter topologies for traction applications, showing that there is a possibility to increase the voltage levels, by inserting an extra number of sub-modules. In this way, it is possible to reduce the size of the passive filters, developing more compact and energy-efficient solutions. Additionally, they are scalable solutions, robust and widely presented in the literature. However, it should be noted that although the catenary interface converter modules are connected in series, as shown in Figure 2, the power converters share the same DC-bus at the low voltage side. This feature not only facilitates control algorithms but also enables the integration of other power electronics converters to interface an ESS or renewable energy sources. From a commercial point of view, the fact of sharing the same DC-bus and having several fully controlled power semiconductors referenced to the same reference point makes it possible to implement simpler and cheaper driver circuits.

By integrating the MMC into railway systems, it is possible to develop power electronics solutions without the need for low-frequency transformers. By integrating semiconductors with higher switching frequencies, it is applicable to decrease the size of the passive filters. Consequently, reducing the volume, the weight and the cost of implementation compared to the conventional power converter solutions. Despite the high switching frequency increases the conduction losses, it is possible to decrease core losses of inductive elements. Being a modular system, it is easy to adapt as well as to replace damaged modules. However, redundant protection mechanisms can be developed, safeguarding the integrity of the railway system and/or power electronics converters [29]. The MMC can be integrated in different railway solutions, for instance, to fully supply the locomotives through a Static Frequency Converter (SFC) [30], or for power compensation applications as presented in [28], [31], [32]. Since the concept of MMC is quite recent and with the constant increase of the operating powers of the railways, there are different challenges in the design of this type of solution. The biggest challenge from a practical and modular standpoint is the control system. Taking into account the catenary voltages and a maximum voltage blocking power of 6.5 kV of the commercially available power semiconductors (IGBT), more than 12 cascade modules would be required. If each module consists of a half-bridge DC/AC power converter, the control system would have to control 24 PWM signals or 48 PWM signals if the modules were comprised by full-bridge DC-AC power converters. This also lacks the necessary PWM signals for the other converters, such as the DC-bus interface, renewable energy sources and ESS. Given these numbers, a conventional 24 PWM signal Digital Signal Controller (DSC) cannot control the system on its own, and auxiliary control techniques must be implemented or other microcontrollers should be included in the system. Thus, it is possible to highlight that constitutes the MMC, with a management layer (Master) and control of each slave. However, each module would thus consist not only of the power electronics circuit, but also a dedicated microcontroller capable of controlling the semiconductors and acquiring the signals to be controlled, sharing a communication bus with the remaining slaves and master. This would make it possible to implement a fully modular solution. In case of implementing the system with a Field-Programmable Gate Array (FPGA) and if it is necessary to insert more modules, it will be necessary to reconfigure the FPGA peripherals, losing the concept of modularity.

One of the emerging concepts lies in the inclusion of solid-state power transformers to replace conventional low-frequency interface power transformers. Once again, with the inclusion of power electronics, it would be possible to

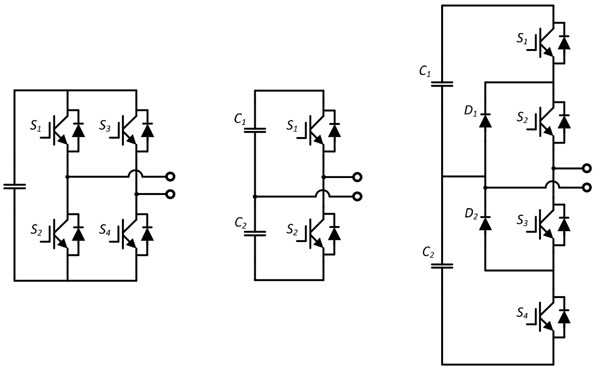


(a)

(b)

(c)

Figure 2 – Most common MMC configuration used for railway traction (based on [29]).



(a) (b) (c)

Figure 3 – Most common used topologies in different MMC configurations by the railway traction suppliers: (a) full-bridge; (b) half-bridge; (c) Neutral-Point Clamped (NPC).

increase the switching frequencies allowing the size of passive filters to be reduced and thus to develop more compact and lightweight solutions. In addition, the solid-state transformer allows for more dynamic control of system variables, which attenuates the degradation of power quality and increase the reliability. Nevertheless, it assists in the implementation of system detection and protection mechanisms as well as enables the energy flux control [33].

IV. CONCLUSIONS

In this paper, several power electronics solutions for the railway power systems were highlighted, including the advantages, disadvantages, opportunities, challenges and future trends. The emerging concepts may enable the creation of more efficient railway systems, resulting in a promising future for the railway industry. The development achieved in the last decades regarding the sensors industry has been reflected in the railway industry as well, leading to strong growth in sensing and controlling systems of trains that allow continuous monitoring and control. This opens the door to a new spectrum of features, such as bidirectional power flow (either between locomotives or between Energy Storage System) and the possibility of different energy sources to supply the railway system. The new possibilities make the railway system more efficient and more energy independent of the power grid. Different concepts to be implemented in the short and medium-term were presented, as well as more revolutionary concepts with longer-term use. The adaptability between the new concepts and the existing solutions has also been highlighted. For the design of these ideas, it is necessary to develop power electronics solutions for high power operation, and the multilevel converters concept has been under interest for such applications. In the last part of this article, a review of the state of the art is presented, as well as the most commonly used configurations of power converters in railway systems, highlighting the challenges and trends.

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