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Review

A Review of the Energy Efficiency Improvement in DC Railway Systems

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Abstract: This study is focused on the topical issue of increasing the energy efficiency in DC railway systems, in the context of global concerns for reducing the CO_2 emissions by minimizing the energy consumption and energy loss. The main achievements in this complex issue are synthesized and discussed in a comprehensive review, emphasizing the implementation and application of the existing solutions on concrete case studies. Thus, all specific subtopics related to the energy efficiency are covered, starting with power quality conditioning and continuing with the recovery of braking energy, of which a large part is lost in the classic DC-traction substations. The solutions of onboard and wayside storage systems for the braking energy are discussed and compared, and practical examples are given. Then, the achievements in transforming the existing DC-traction substations in reversible substations with capabilities of power quality improvement are systematically reviewed by illustrating the main results of recent research on this topic. They include the equipment available on the market and solutions validated through implementations on experimental models. Through the results of this extensive review, useful reference and support are provided for the research and development focused on energy efficient traction systems.

Keywords: DC-traction; energy efficiency; power quality; braking energy recovery; onboard energy storage; wayside energy storage; reversible substation

1. Introduction

Nowadays, DC-traction systems are preferred and extensively used in urban railways and suburban or mainline services like light and heavy metro trains. The most common DC-traction voltages for the respective systems: 600 V used mainly by tramways and underground systems (e.g., older trams in Brussels, Helsinki, and Amsterdam); 750 V (e.g., modern trams/metros/light rail in South London, Genova, Bucharest, and Los Angeles County); 1500 V used mainly by metros and suburban lines (e.g., in Roma, Madrid, Melbourne, Japan Railways); and 3 kV (e.g., in Rio de Janeiro suburban network, Slovenian, and Ukrainian Railways).

The transformer-rectifier substations include usually uncontrolled rectifiers, whose pulse number is determined by the traction transformer windings and the static converter configuration [1–4]. The common schemes are 6-pulse [5,6], 12-pulse [7–11], and even 24-pulse diode-based rectifiers [11–13]. The use of controlled rectifiers in the traction substations (TSs) was considered much later. Thus, the first thyristor controlled rectifier (TCR) was put into service by Dallas Area Rapid Transit (DART) in the early nineties to take advantage of the DC voltage control, fault current limiting and leading to improved performance in terms of speed, reliability, and lower energy losses, as well as to the possibility of increasing the distance between TSs [14,15]. A TCR was also installed by the Long Island Rail Road (LIRR) for experimental use in 2003 [14,16]. The possibility of switching from TCR to reversible TCR (RTCR) with capability of power recuperation into the AC line was then prefigured. Despite the widespread use of the Insulated-Gate Bipolar Transistors (IGBTs) in high-power converters, their significantly higher losses and costs compared to TCR-based rectifiers must be taken into account when choosing the IGBT-based rectifiers [17]. Nevertheless, the capabilities of a PWM rectifier in terms of bidirectional power flow and almost unity power factor, in both rectifying and braking modes, have been proven [18].

In recent decades, a constant concern and challenge in industrial and academic research is finding and implementing new solutions and approaches to increase the energy efficiency in DC railway traction systems. It is generated by the awareness of the need for significant improvement in power quality (affected by the operation of the traction rectifier), reducing the CO_2 emissions by reducing energy consumption, or reusing the regenerative braking energy to the fullest extent possible.

As with all nonlinear loads in electrical systems, the power quality has been, and remains, an important and frequently investigated problem in the electric traction systems. Compliance with the limits stipulated in specific standards and recommendations related to harmonic pollution, such as IEEE-519-1992 (last updated in 2014) [19], and the total compensation of reactive power, harmonics, and imbalance at the power supply side are the main concerns. Ensuring a higher power factor at the power supply side leads to lower supply current and associated losses, which is reflected in increased energy efficiency. Comprehensive reviews and perspectives of the power quality issue in the AC traction systems are provided in [20] and [21]. Various devices in the category Flexible Alternating Current Transmission Systems (FACTSs), including the static synchronous compensator (STATCOM) and railway power quality conditioner (RPC), are reviewed in [22]. As FACTS devices are based on active switching components, they are able to provide dynamic compensation response. Lao, Wong and Santoso presented STATCOM, consisting of a three phase voltage source converter, which is intended for the unbalance compensation in a high speed traction system [22]. Its ability to provide reactive power compensation is also mentioned. The RPC, which consists of two single-phase converters with a common DC link and can be regarded as a two-phase STATCOM, is designed to be connected at the secondary side of the substation transformer. It is considered to be a unified solution of reactive power, system unbalance, and harmonic problems in railway traction [22].

However, few papers in literature are directed on the power quality issue in DC traction systems. They mostly consist of investigations, monitoring activities [23,24], and solutions proposals for conditioning based on tuned passive harmonic filters [25,26], hybrid structures with static VAR compensators (SVCs) [27], or active power filters (APFs) [28,29], validated by simulation. Moreover, there is a lack of review papers on this topic.

Another topic in energy efficiency in the last years refers to the traction power management by the most efficient usage of the energy during all stages of operation, especially in urban rail transit [30–36]. To minimize the tractive energy consumption, the strategy of energy-efficient driving ensures the optimization of the speed profile at each section [31,35,36]. Inevitably, most of strategies involve a more efficient management of the regenerative braking energy. As known, the DC-traction line is not always receptive. Therefore, the remaining recovered energy, after covering auxiliary service needs, can only be sent back to the DC network when another train accelerates in the same section. If there is no accelerating train at that time, this feedback energy is wasted by braking resistors. Thus, synchronizing the accelerating and braking of trains through a timetable optimization is a simple way to improve the use of regenerative energy [31,33,36,37]. A simple way to recover the kinetic braking energy is to store it as potential energy even in the mass of the vehicle, by raising platforms in the railway stations. It involves changes in the existing railway track or designing the new tracks appropriately. Moreover, by adopting energy-efficient system design strategies, such as the good design of gradients through optimized slopes distance, additional energy savings can be obtained [38,39]. As Su et al. concluded in [39], the energy saving is ~2% in the case of Beijing Yizhuang metro line. There are also a new tendency of complex integrated approaches considering the energy-efficient driving and timetable optimization in the same optimization problem [35–37]. Getting energy-efficient traction systems through some measures, such as reducing energy losses in the power supply network and onboard traction equipment, vehicle mass reduction, reducing the energy consumption of comfort functions, and infrastructure-related measures, is also possible [32]. This particular topic is not intended to be developed in this paper.

The onboard and stationary energy storage systems (ESSs), involving an electric storage medium, such as a supercapacitor, battery, or flywheel, are topical solutions to exploit the regenerative braking energy in DC railway systems. They are subject of some recent review papers [40–42]. As Hayashiya et al. from reputable railway companies in Japan (East Japan Railway Company, Tobu Railway Co. Ltd. and Tokyo Monorail) specified more than 20 ESSs have already installed in the Japanese DC traction system by 2017 [41]. As a confirmation of these emerging technologies to improve the power supply receptivity, the first IEC standard, namely IEC 62924:2017, specifies the requirements and test methods for a stationary ESS to be used in a DC traction railway in order to store the energy and supply it back to the DC network when necessary [43]. It is clearly specified that it does not apply to onboard ESSs.

In maximizing the reuse of regenerative braking energy, an alternative to using storage systems is to transform the existing TSs into reversible substations, also referred as bidirectional, inverting, or active substations. Through this solution, the surplus of regenerated energy is driven back to the main AC power supply. Since the AC network is permanently receptive, there is the possibility of full braking energy recovery, excepting the inherent losses in transporting this energy back to the grid. Although there are many papers on the topic of reversible substations focused on different implementations, such as [44–49], there are few topical synthesis papers. A very recent review on the methods used for regenerative braking energy recovery, including the reversible substations, is presented by Khodaparastan in [50]. Thus, the possibilities of combining the existing diode rectifier with an antiparallel inverter or of replacing the existing diode rectifier by a reversible thyristor-controlled rectifier are illustrated. Some worldwide representative implementations of reversible substations, such as Alstom-HESOP, Siemens-Sitras TCI, and Ingeteam-INGEBER, are summarized too. An extensive synthesis, including the control system and coupling filters on the DC and AC sides, is intended to be achieved in this paper.

The interest of practitioners in increasing the energy efficiency of electric railways systems is also illustrated by special issues of journals on this specific topic, as is the one in 2010 called "Energy saving technologies on electric railways in Japan". Reducing the losses and increasing the regenerative energy are the main goals in the proposed energy saving technologies [30,51–53]. Besides, several projects have been initiated in recent years with the objective of reducing the energy consumption in urban railway areas, in order to reduce CO_2 emissions.

The International Union of Railways (UIC), through its subcommission "Energy Efficiency", initiated, in 2001, a project where all relevant railway energy-saving technologies should be analyzed, categorized, and evaluated. As part of this action, all findings are being fed into a database and provided by a user-oriented communication tool, in order to enable the user to have an overview of the energy-efficiency potential. Currently, the database contains 97 technologies and 55 projects [54].

"Efficacity", which is the Urban Energy Transition Institute in France, that has been operating since 2014 within a partnership between the Research and Development (R&D) center, public and private industrial companies, and engineering consultancies, as well as higher education and research bodies, is aimed to develop and implement innovative solutions to build a future city that is energy efficient and massively low carbon. Achieving high energy performance districts through energy optimization in the railway stations and maximum use of the recovered braking energy are major concerns in the purview of the Institute. Storage the braking energy of the trains, by means of a stationary electrical saving system, and integration into the railway station power supply thanks to a microgrid, is the basic idea within one of the projects [55–57].

There are other projects carried out in recent years focused on reuse of regenerative braking energy.

The OSIRIS (Optimal Strategy to Innovate and Reduce energy consumption In urban rail Systems) FP7 research project, with 17 partners belonging the public transport operators, railway manufacturers, and universities, was conducted from 2012 to 2014. It aimed at enabling a reduction of the overall energy consumption within Europe's urban rail systems of 10%, compared to current levels, by 2020 [50,51]. In the focus of "Energy Efficient Vehicle and Infrastructure Related Technologies", the main achievements were "New concept of onboard energy storage system for tram tested in Vitoria-Gasteiz" and "Innovative auxiliary converter for metro trains installed in Milan" [58–60].

Ticket to Kyoto (T2K) was another European project over four years (from 2010 to 2014), which aimed at reducing CO_2 emissions in the public transport sector through more environmentally friendly behavior and improvements to transport-related infrastructure. A group of five urban transportation companies (MOBIEL-Bielefeld, RATP-Paris, RET-Rotterdam, STIB-Brussels, and TFGM-Manchester) cooperated on different pilot projects within T2K, and more than half of the T2K budget was dedicated to investments to improve the energy efficiency of transport infrastructure. Three of the T2K partners have simultaneously implemented the investigated braking energy recovery technologies on their networks. For STIB, the INGETEAM inverters to be installed along the Brussels metro network were the best solution. MOBIEL opted for energy storage technology through one flywheel from PILLER and reversible substation through two inverters from INGETEAM. RET decided that a reversible substation is the best option for the metro network in the Rotterdam area and two reversible substations were designed and implemented [46,61,62].

The action plan of achieving energy savings at no cost developed by The Southeastern Pennsylvania Transportation Authority (SEPTA) as part of a broader environmental sustainability strategy is another example of a successful project. SEPTA and Viridity Energy, a Philadelphia-based smart grid firm, have devised a way to capture, store, and reuse the regenerative braking energy building on the idea of large-scale storage battery (Intensium Max 20P lithium-ion energy storage system produced by Saft Batteries Inc., Levallois-Perret, France) and a control system (produced by ABB Envitech Inc., San Diego, CA, USA). Thus, between 5% and 25% of the traction energy is recovered. Moreover, through its partnership with Viridity Energy, SEPTA participates in the frequency regulation market and PJM, which is Regional transmission operator, pays a premium for this service [57,63–66].

This paper is intended to provide an up-to-date and comprehensive review on the energy efficiency improvement in DC railway systems, in order to cover the shortcomings found in the literature. The attention is directed on the power quality aspects and the reuse of the regenerative braking energy. The paper is organized as follows. Section 2 outlines the solutions for power quality conditioning in the traction regime of the traction substations. Section 3 outlines a synthesis on the braking energy storage solutions. Then, Section 4, which is the largest part of the paper, is devoted to the reversible substations. An overview on different achievements, implementations, and commercial solutions grouped on categories is presented. Finally, some new trends are summarized and concluding remarks are formulated.

2. Power Quality Conditioning

Figure 1 illustrates the simplified structures of the common DC-traction substations based on six-pulse and twelve-pulse parallel/series uncontrolled rectifiers and the associated waveforms of the phase voltages and currents.

Due to the presence of the rectifiers, the harmonic distortion of the current on the AC-side is the main problem, unlike the AC traction systems where the undesired system unbalance is the main concern. The harmonic distortion level is high, the more so as the number of pulses of the rectifier is lower. In terms of the total harmonic distortion factor (*THD*), the range is of approximately 10 to 30% in the absence of the compensation measures [6,8,67,68].

Achieving a current harmonic distortion below the well-known limit of 5% provided by IEEE-519 standard [19] is the main purpose in adopting the compensation measures. Even if the traction rectifiers are diode-based, there is also a small reactive power to be compensated. It must be noticed that if *THD* (which divides the distortion component to the fundamental frequency component I_1) meets the limit, then the total demand distortion (*TDD*) invoked in standard, which divides the distortion component to the maximum demand current I_L, meets the limit too, since I_L is always higher than I_1 [69].

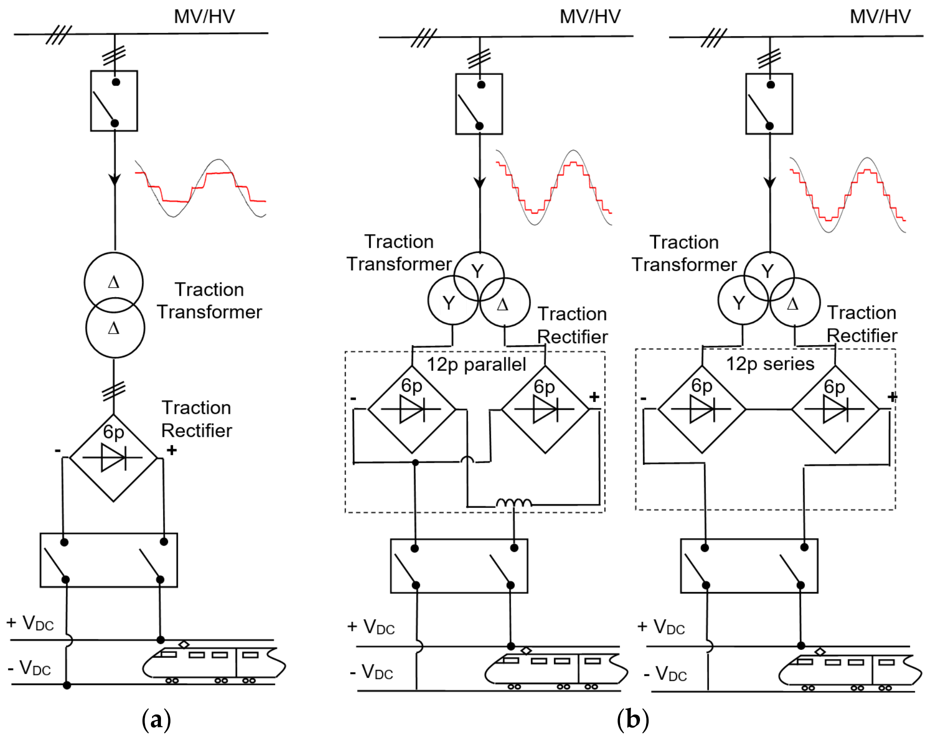

Figure 1. Simplified schemes of the usual DC-traction substations and specific waveforms of the supply phase current and voltage: (**a**) case of 6-pulse uncontrolled rectifier and (**b**) case of 12-pulse parallel and series uncontrolled rectifier.

The cheap and effective solution of passive filters tuned on harmonics 11th and 13th placed in each of the transformer secondary supplying the 12-pulse series rectifier was proposed for a TS located in Tebessa–Annaba, Algeria [25]. To correct the power quality problems in a DC traction system and keep the voltage drop below 5%, as specified in IEEE Std. 141-1993 [70], Martinez and Ramos proposed to add a passive filter together with SVC (a Thyristor Switched Capacitor (TSC) and a Thyristor Controlled Reactor (TCR)) to the distribution network [67].

The development of the active power filters (APFs) as flexible solution of high performance for the global compensation of harmonics, reactive power, and even unbalance, has provided a much more effective alternative to solving the power quality problems, but much more expensive. The most used topology is that of parallel connection, called shunt active power filter (SAPF) which is based on the structure of a voltage source inverter (VSI) (Figure 2a). Moreover, through hybrid structures consisting of passive filters and SAPFs, the advantages of both types of filters are used with lower costs (Figure 2b). Examples of using a SAPF and a hybrid structure (SAPF and passive filter tuned on 5th and 7th harmonics) in DC-traction substations are provided by Ramos et al. [28] and Hosseini et al. [29]. Obviously, the proper control of the VSI in the structure of SAPF is the key for obtaining very good performance. In both implementations, the generation of the reference compensating current is based on the so-called p-q theory of the powers [71], which can be applied successfully even under nonsinusoidal voltage conditions [72,73]. Regarding the control of the current provided by SAPF and the voltage at the DC-side, the simple, quick, and robust hysteresis band strategy and Proportional Integral (PI) ensure very good performance [29,72]. Clearly, any technique and control strategy conceived for a SAPF can be applied in the particular case when the nonlinear load is a DC-traction substation.

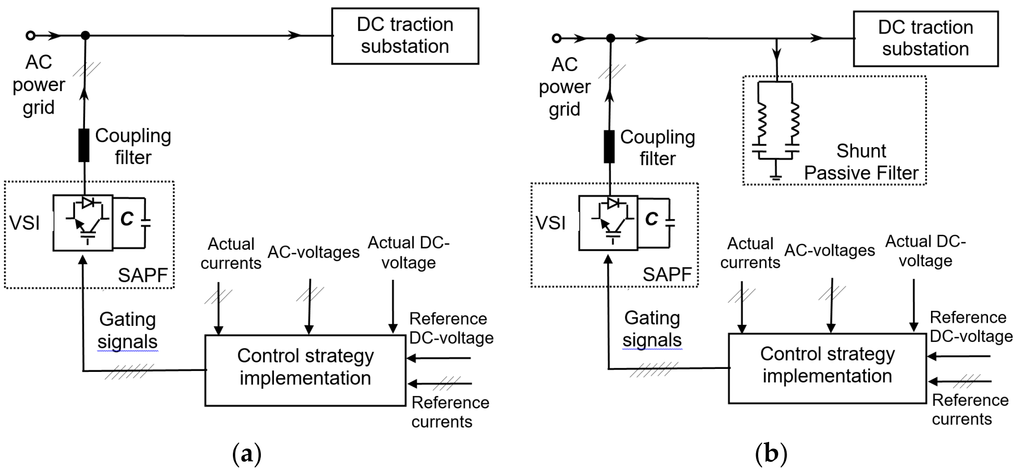

Figure 2. Structure of shunt active power filter (SAPF)-based compensator used in DC-traction substations: (**a**) simple SAPF and (**b**) hybrid compensator.

As shown in Section 4, a step forward in solving the power quality issues during the operation in traction regime is a benefit that can be provided by transforming the DC-traction substation into a reversible one, by adding a properly connected and controlled VSI between the catenary line and the AC line [6,45,74,75].

3. Braking Energy Storage Solutions

A properly designed braking energy storage system is able to capture and store the braking energy of the vehicle during the deceleration in order to be used later, when needed.

Three type of ESSs are generally used for this purpose—batteries (most often of type lead-acid, nickel-metal hydride (Ni-MH), or lithium-ion (Li-ion)), supercapacitors (also referred as EDLCs (electrochemical double layer capacitors) or ultracapacitors) and flywheels (electromechanical ESSs). More recently, combinations of batteries and supercapacitors are taken into consideration [76]. The factors that decide the best choice of technology refer mainly to the energy capacity, the charge/discharge rate and the life cycle [50,77].

As regards the ESS's connection to the DC-line, the presence of a DC/DC converter is strongly recommended in case of supercapacitors, to fully exploit their large voltage window, to reduce the charge/discharge current peaks, as well as peaks to control the state of charge over time [78].

Depending on where they are installed, there are both mobile ESSs (called also onboard ESSs) and stationary ESSs (called also wayside ESSs). The first ones are mostly located on the roof of each train, whereas the others in specific locations along the trackside.

3.1. Onboard Storage Systems

Through the onboard ESSs, there is a significant contribution to the energy saving in railway systems, since the energy they store during the braking process can be used to power the vehicles themself during the next accelerations. Due to the line losses absence, there is a higher efficiency during operation, compared to the wayside ESSs.

The main benefits of using onboard ESSs refer to the possibility of minimizing the power peaks during acceleration of vehicles, stabilization of the supply voltage, and the gain in power autonomy in catenary-free operation [31,33,51,76].

There are also important drawbacks in using onboard ESSs, such as the need for a large installation space in each vehicle and increased weight, leading to the increasing of the traction energy consumption by up to 2%. That is why the onboard ESSs are preferred in designing new vehicles, rather than in retrofitting the existing rolling stocks [31,33,79].

Some examples of onboard ESSs implementation are given in Table 1. It can be seen that most of them are based on supercapacitors. When large degree of autonomy is needed, the use of high power Li-ion and NiMH batteries is a better option. As for the use of flywheels in onboard ESSs, ALSTOM abandoned the project for the Citadis tram in Rotterdam due to technical reasons [61]. There are some limitations related to safety and cost, due to which this solution attracted less attention.

Table 1. Examples of onboard energy storage system (ESS) implementation.

Technology	Provider, Commercial Product	Applications	References
Supercapacitor	Bombardier, MITRAC Energy Saver	Light rail, Mannheim (Germany), 750 V, 2003	[33,40,50,61,80,81]
Supercapacitor	Siemens, Sitras MES	Tram in Innsbruck (Austria)	[31,33,61]
Supercapacitor	CAF, ACR system	Tram in Seville, Saragossa, Granada (Spain)	[33,61]
Supercapacitor	Alstom, STEEM	Tram in Paris (France), 2009	[31,33,61]
Li-ion	Kinki Shayro, LFX-300, streetcar	Charlotte (North Carolina USA), 2010	[31,33,61]
Ni-MH	Alstom – Saft	Tram in Nice (France), 2007	[31,50]
Flywheel	Alstom & CCM, Citadis	Tram in Rotterdam (Rotterdam), 2004	[33,82]
Hybrid Supercapacitor + Ni-MH	Siemens, Sitras HES	Light rail, Lisbon (Portugal), 750 V DC, 2008	[33,61,79]

3.2. Wayside Storage Systems

In the case of wayside ESSs, the accumulated braking energy comes from any train nearby, and it is released when a power demand is detected.

Compared to the case of onboard ESSs, there is no restriction of installation space and weight, but the line transmission losses are higher. Thus, attention must be paid to the position of the storage equipment within the trackside. A benefit of wayside ESSs is the ability of minimizing the problems related to voltage sags [50,83]. Moreover, a wayside ESS can be designed to ensure fast frequency regulation and to provide energy in the local electricity market [63].

Examples of wayside ESSs implementation are illustrated in Table 2. Although supercapacitors are the most common, the Li-ion and Ni-MH high-power batteries are also commercialized, more so than in the case of mobile storage systems. The flywheels are more used in the stationary ESSs, as they can be placed in containers or underground [33].

Table 2. Examples of wayside ESS implementation.

Technology	Provider, Commercial Product	Applications	References
Supercapacitor	Siemens, Sitras SES	Bochum, Cologne and Dresden (Germany), Madrid (Spain), Beijing (China), 600V, 750V	[33,61]
Supercapacitor	Envitech Energy (ABB group), Envistore	Warsaw (Poland), Philadelphia (Pennsylvania)	[31,64]
Supercapacitor	Meiden, Capapost	Hong Kong	[31]
Li-ion	Hitachi, B-CHOP	Kobe (Japan)	[31,84]
Li-ion	Saft, Intensium Max	Philadelphia (Pennsylvania)	[31,85]
Ni-MH	Kawasak, Gigacell BPS	New York City (USA)	[31,86]
Flywheel	Kinetic Traction Systems, GTR system	London (UK), New York (USA), Lyon (France)	[31,87]
Flywheel	Vycon, Regen system	Los Angeles (California)	[31,50]

The necessity and benefits of energy storage systems has been grounded for many case studies, for example,

- the tram in Liberec, Czech Republic—through a mechanical flywheel with a motor generator and its connection to the main bus bar in substation [88];
- the tramline in Bergamo, Italy: the stationary systems are the best choice from the cost/benefit point of view; the connection to the line by a DC/DC converter allows better managing the storage systems and the high power lithium batteries appear much more competitive than the supercapacitors [78];
- the high-speed line from Florence to Rome (“Direttissima” line), for which the use of stationary and onboard batteries and supercapacitors has been considered, leading to the conclusion that the storage systems based on lithium batteries, either stationary or onboard, are suitable in terms of cost-effectiveness [42].

In a white paper published in 2018, the interest of New York City Transit (NYCT) in application of wayside energy storage systems for recuperation of regenerative braking energy is expressed [85]. Consolidated Edison Inc., one of the largest investor-owned energy companies in the United States, can utilize the stored energy for network or system needs. The analysis shows that the average regenerative energy produced during deceleration can reach about 50% of the acceleration energy. It is highlighted that supercapacitors and flywheels are comparably suitable for this application, whereas a battery is more cost-prohibitive. Intention to evaluate the alternative solution of reversible substations is expressed too.

Simulation-based on specific models and comparison with the real measurements are useful tools in the precise quantification of the regenerative energy and the optimal design of an ESS and/or a reversible substation. [85,89].

4. Reversible Traction Substations

The concept of the DC reversible substation has emerged from the need to improve the power line receptivity, so that the braking energy can be regenerated to a greater extent. Improved power quality at the power supply side is also required. The regenerative braking energy is sent back to the upstream AC grid to be consumed by other electric AC equipment in the substation or even to the main grid based on the legislations and rules of the electricity distribution network [50].

The main functions to be fulfilled by a reversible substation are [31]

- to leave priority to the natural exchange of regenerated energy between vehicles;
- to minimize the level of harmonics, ensuring a good quality of power supply in both AC and DC sides;
- to maintain the output voltage in traction and regeneration regimes.
- In order to get the capability of allowing reverse power flow in a common DC-traction substation equipped with uncontrolled rectifier, an inverter must be connected in antiparallel with the rectifier. Thus, the existing group consisting of traction transformer and diode rectifier is kept and the energy recuperation ability is gained with minimal equipment. Depending of the type of chosen inverter, the static converter ensuring the bidirectional energy flow may consist of [50,90];
- diode rectifier and thyristor-based inverter, also referred as thyristor line commutated inverter (TCI);
- diode rectifier and pulse-width modulation (PWM) inverter based on fully controlled switches.

When the system upgrading is accepted, the uncontrolled traction rectifier can be replaced by a four quadrant converter. It can be, for instance, either the reversible thyristor controlled rectifier [90], a thyristor rectifier bridge associated with an IGBT converter [91], or an IGBT-controlled rectifier/inverter bridge [92]. Consequentially, the need to replace the existing transformer makes this solution more complex and costly.

Obviously, in the new designed DC-traction substations, a bidirectional converter of high performance can be considered from the beginning.

Different approaches in implementing the reversible DC-traction substations, including the main systems available on the market, are summarized below.

4.1. Reversible Substations with Diode Rectifier and Thyristor-Based Inverter

A representative commercial solution in this category is Sitras-TCI provided by Siemens, which is illustrated in Figure 3 [61,93].

Through Sitras-TCI, the braking energy is recovered and transferred in the permanently receptive medium voltage power grid at any time and over long distance.

The current ratings of TCI are about half of the forward rectifier [90].

As shown in Figure 3, the components of the TCI are included in a panel group to be easily integrated into existing substations.

For the version of 750 V, the autotransformer is already integrated, whereas for the version of 1500 V, as well as for the 750 V version of higher power, the autotransformer must be installed separately [93].

It must be specified that the autotransformer is needed to increase the AC voltage by 10 to 15%. By using the DC reactors, the circulating current between TCI and diode rectifiers can be limited [50,90].

Regarding the Sitras-TCI implementation in real DC-traction substations, the 750 V system was tested in the Oslo metro and the new Singapore downtown line. A real application of the 1500 V version can be found in Germany: the Bayerische Zugspitzbahn Bergbahn Railway [31].

To the best knowledge of the authors, no details on the Sitras-TCI control and saving energy have been reported so far.

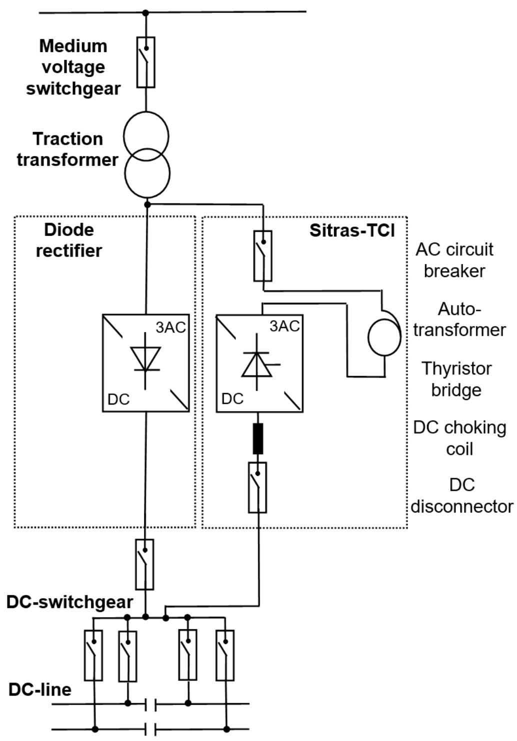

Figure 3. Schematic diagram of the Sitras TCI integrated into an existing DC-traction substation with uncontrolled rectifier [61,93].

4.2. Reversible Substations with Diode Rectifier and PWM Inverter

Based on the same add-on concept as Sitras-TCI—meaning that the diode rectifier in the traction substation is preserved—the solution of antiparallel PWM inverter is often found in literature.

The PWM inverter provides a reverse path for the recovery energy and it has the advantage of being able to operate under unity power factor conditions by a proper control. However, it should also be mentioned the disadvantage of higher switching losses and converter size and costs, when compared to TCI. As an example, the INGEBER system supplied by Ingeteam Traction in Bilbao has 1.5-MW peak power and requires a 7.5-m^2 footprint area, compared with the footprint of 2.4 m^2 associated to the Siemens-TCI at a higher peak power of 3 MW [90].

Regarding how to connect the inverter to the existing system, in order to ensure good performance in both traction and regeneration regimes, a proper correlation between the inverter voltage at the DC-side and the AC voltage in the point of common coupling (PCC) must be ensured [94]. To illustrate the capability of scheme to allow the regeneration and compensation through the connection of the

PWM inverter in the transformer secondary, the ratio k_p of the rated DC voltage (U_{DCN}), and the magnitude of the line-to-line voltage in the transformer secondary is expressed as [94]:

$$k_p = U_{DCN}/\left(\sqrt{2}U_S\right) = k_R/(1+\delta U), \tag{1}$$

where U_S is the rms voltage in the traction transformer secondary, δU is the DC voltage drop expressed as a percentage of U_{DCN} (approximately 5 ÷ 10%), and k_R is a coefficient depending of the type of rectifier, respectively.

- $k_R = 3/\pi = 0.955$ for the three-phase bridge rectifier and for the 12-pulse parallel rectifier.
- $k_R = 6/\pi = 1.91$ for the 12-pulse series rectifier.

The condition that U_{DCN} must exceed the magnitude of the line-to-line voltage in PCC to obtain a good quality of the current injected by the inverter acting as SAPF [95,96] will only occur when k_p is over unity and the inverter can be connected directly in the secondary of the traction transformer. Thus, considering δU = 10% for instance, the resulted values of k_p for the common rectifiers in the DC-traction substations are

- k_p = 0.87 for the three-phase bridge rectifier and for the 12-pulse parallel rectifier.
- k_p = 1.74 for the 12-pulse series rectifier.

Thus, only the TSs with 12-pulse series rectifiers allow the regeneration and compensation by using the traction transformer.

In order to obtain the correct correlation between U_{DCN} and U_S, either the DC voltage at the inverter input must be increased by means of a boost chopper or the inverter must be connected to PCC by means of a dedicated transformer/autotransformer having a lower voltage on the inverter side [90,95,97].

Gelman estimated that the losses in the PWM inverter and the boost DC/DC converter are ~6 times higher than in TCI's thyristors at the same current, thus illustrating one of the drawbacks of using a PWM inverter [90].

There are implementations of both variants of adapting the DC and AC voltages in literature.

The use of a boost DC/DC converter was adopted in the commercial solution called INGEBER conceived and developed by INGETEAM Traction.

4.2.1. The INGEBER Solution

As illustrated in Figure 4, the INGEBER system of the INGETEAM Traction Company is made up of a boost chopper in series with a PWM inverter, connected between the catenary and the traction transformer secondary, in parallel with the traction rectifier [96,98,99]. Coupling filters of L type are used on both AC and DC sides.

Continuous monitoring of catenary's state is provided so that when there is energy to be recovered, the proper conversion to AC energy is achieved and high quality AC current is injected to the three-phase power supply. A harmonic free current in the three-phase grid in traction regime is also ensured, even during power consumption peaks [61,96]. To the best of our knowledge, there are no details in literature on the control system.

To guarantee the reliability of the whole system, the converter is designed to enable its self-isolation from the substation without compromising its operation, by a proper disconnection from both the DC and AC sides [99].

The INGEBER system was first implemented in the Bilbao Metro in 2009 on Ripa Substation under 1500 V DC catenary voltage. Then, another four INGEBER were installed in Bilbao Metro. Other implementations are reported in the suburban railway in Fuengirola Malaga under 3000 V DC and in Metro Brussels under 750 V DC. IGBTs are used as power semiconductor devices in the structure of the PWM inverter [47].

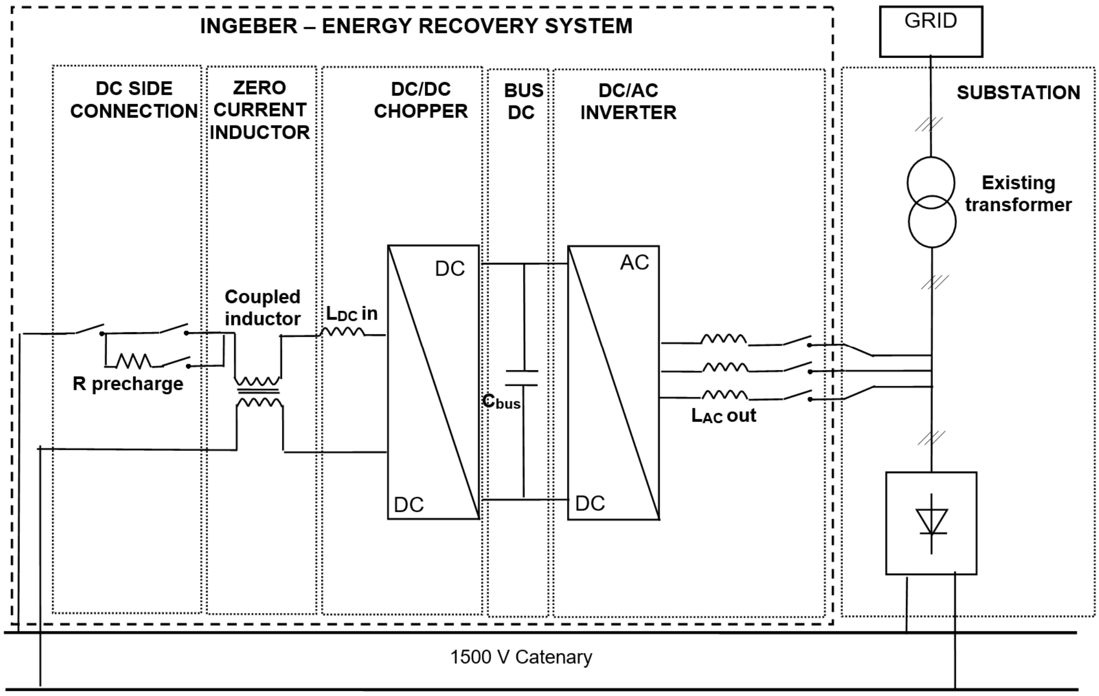

Figure 4. Schematic diagram of the INGEBER system integrated into an existing DC-traction substation with uncontrolled rectifier [96,99].

4.2.2. The Enviline ERS Solution

The Enviline Energy Recuperation System (ERS) is a wayside energy recuperation system provided by ABB consisting of an IGBT-based inverter to be connected in antiparallel with the existing substation's diode rectifier, to return the surplus of braking energy to the main grid [50,100]. Thus, the total energy consumption of the traction substation can be reduced by up to 30%, depending on the operating conditions of the train system [100].

As expressed in its presentation by the supplier, the ERS system operates on 600, 750, and 1500 V, and can be configured to ensure the rectification boost operation and the reactive power mitigation during the operation in traction regime. A low harmonic content of the current is expected ($TDD < 5\%$) [100].

The Enviline ERS was installed in Poland on the Łódź tram network in 2013 [33].

4.2.3. Other Implementations of the Reversible Substations with Diode Rectifier and PWM Inverter

For a DC-traction substation equipped with a 12-pulse series rectifier, the solution presented by authors from Korea for a regeneration inverter system with an active power filter ability consists of adding an IGBT inverter between the DC-line and AC grid through an LCL filter and a specific transformer ([44,101]). The coupling interface on the DC-side is no specified. As regards the control system, the synchronous reference frame method is used for the operation in regeneration mode and the p-q theory for the operation in APF mode. Good results are obtained on a prototype model, in which a pure inductive coupling fitter is provided.

A full-scale prototype of multilevel series-stacked converter system of 1.5 MW was built with IBGTs and installed at a DC-traction substation by South Africa's railway company, Spoornet. Both regeneration and APF functions of the system were successfully implemented, but a remaining harmonic distortion of the current (~15%) in the APF mode was reported, which is quite high [45].

The so-called Buddy bidirectional supply for TSs equipped with 12-pulse passive rectifiers was developed by IMTECH company (Barendrecht, Netherlands) to give the possibility of energy feedback with minimal changes in the existing installation [10]. Actually, an IGBT-based active rectifier bridge, referred as Active Front End, and a simple transformer with a single secondary winding are added to the already installed passive rectifier. The control system stabilizes the DC voltage under dynamic load conditions and the implemented current control is of hysteresis-band type [10].

The concept of Buddy bidirectional converter and control was then practically implemented through a so-called Active Regeneration Unit (ARU) at two locations of the metro network in Rotterdam [46] under 750 V rated voltage of the contact line. To limit the slopes generated by the IGBTs' switching, a line filter of LC-type is used.

In the case of a hybrid traction power supply system for urban rail transit, consisting of diode rectifier and IGBT inverter, a droop control method based on load current feed-forward was proposed in [13]. Thus, the load distribution between the reversible converter and the existing 12-pulse diode rectifier is achieved. It was successfully verified by the field test carried out on Beijing Metro Line and 11.15% average energy-savings was reached.

For the case study of Massena DC power station in Paris, which is surrounded by two other power stations operating under 1.5 kV DC voltage, the quantification of the energy that might be recovered with an additional IGBT-based inverter was performed by simulation in [102]. As a result, ~7 kWh could be recovered in twelve minutes.

A comprehensive presentation of a system for active filtering and regeneration in DC-traction substations named SISFREG, through design, control, and implementation issues, is found in the flow of publications in journals and international conferences proceedings. The research was conducted in Romania since 2014 in the frame of an applied research collaborative project through a partnership between University of Craiova and INDA company, in the priority area of energy.

In setting-up the structure of SISFREG (Figure 5), which is intended to be added to an existing DC-traction substation with six- or twelve-pulse series/parallel diode rectifier in order to be transformed into a reversible substation with compensation capabilities, it was assumed that a VSI-based SAPF is the basic component, provided it is properly designed and connected. The intrinsic SAPF's capability of providing an increased voltage on its DC-side ensures the correct operation of the system in terms of the quality of the injected current [94,103]. The possibilities of connecting SISFREG to the power supply on the AC-side are illustrated, supported by a theoretical grounding [94]. Thus, the direct connection in the traction transformer secondary in the case of TS with twelve-pulse series rectifier and the connection to the AC main grid via a dedicated recovery transformer in the case of TS with six or twelve-pulse parallel rectifier are the adopted solutions.

Besides, the VSI-based SAPF SISFREG includes the coupling interface circuits on the AC and DC sides. On the AC-side, an LCL filter with damping resistors ensures the current dynamics and sufficiently smooth the SAPF's output currents affected by the switching frequency harmonics [103–105]. The DC separating circuit for the connection with the catenary line ensures the decoupling of SAPF from the DC-line when there is no current to be recovered, so that the active compensation of the harmonics and reactive power can be achieved [106].

Regarding the control system of SISFREG, involving the control of the DC-voltage on the compensation capacitor, the generation of the reference currents and their accurate tracking by the real currents, two approaches were implemented. The first one is the direct control of the current supplied by inverter, which involves the generation of the reference current based on the measured load current (downstream of PCC) by making use of the concepts of different theories or specific methods such as the p-q theory of the power [73,107], Conservative Power Theory [108], or Fryze–Buchholz–Depenbrock theory [97]. The other is the indirect control, involving the regulation of the supply current (upstream of PCC), whose reference value is provided by voltage controller. As the supply current in regeneration regime has to be an active current, it was argued that the use of the indirect control is more advantageous and it was chosen in the implementation on an experimental setup [103,109–112]. As shown in Figure 6, a PI voltage controller provides the magnitude of the reference active currents, while a block of synchronizing with the fundamental supply voltage provides the sine wave templates of these currents. Then, a hysteresis band current controller ensures the accurate tracking of the prescribed supply currents.

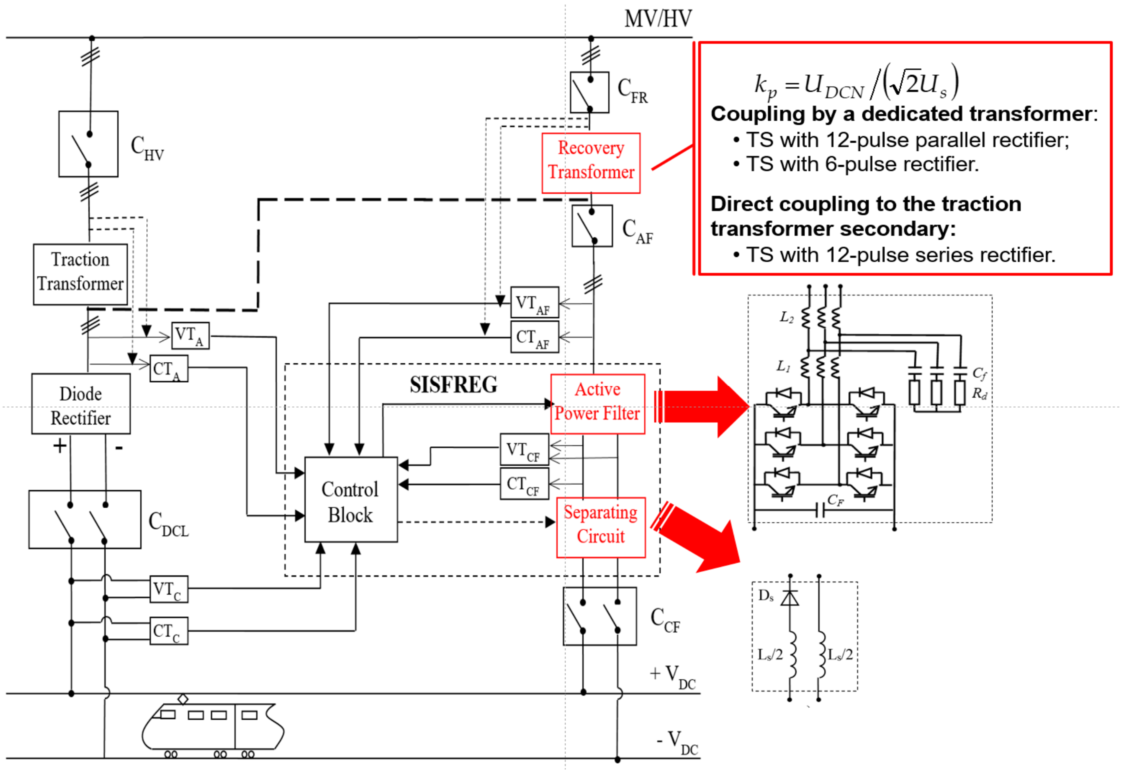

Figure 5. General scheme for connecting SISFREG to an existing DC-traction substation with uncontrolled rectifier [94,103].

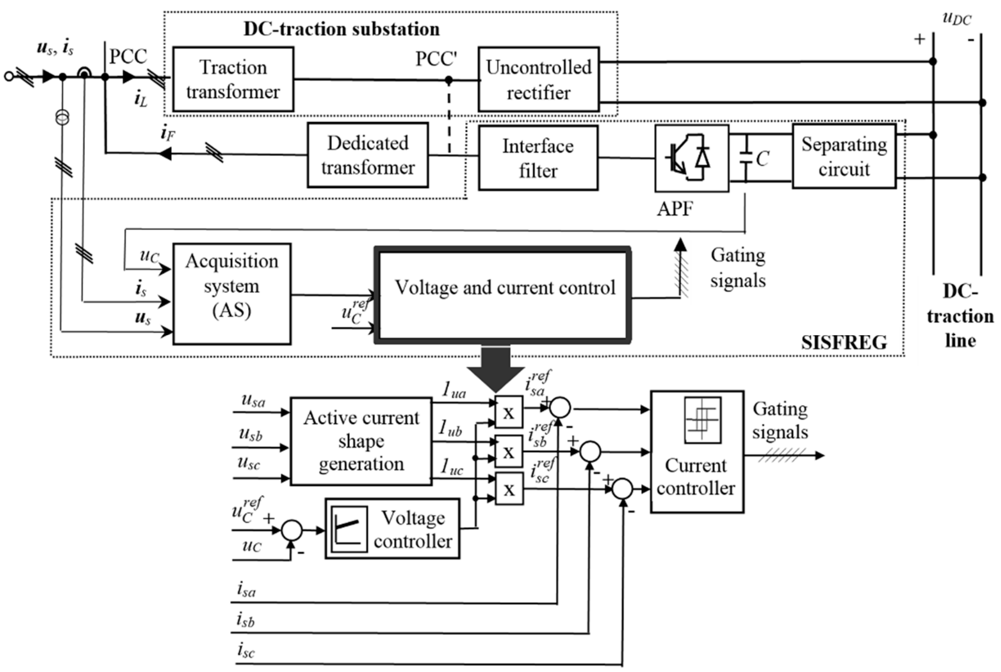

Figure 6. Structure of the indirect control system for SISFREG [103,109].

The main advantages of the thyristor-controlled rectifiers over the diode rectifiers are better voltage regulation and fault current limiting, leading to operational savings, such as energy savings through increased DC-bus voltage and improved service life [14]. Moreover, the number of the traction substations can be reduced, by approximately 15% ÷ 25% in a typical system [16].

4.3. Reversible Substations with Reversible Thyristor Controlled Rectifiers

Compared to TCRs, through the two TCRs connected antiparallel in the structure of an RTCR and the proper designed control system, RTCR is able to transmit the energy either from AC to DC or vice versa, allowing the braking energy recovery. In addition, through desirable voltage control, the voltage regulation, current limiting, and proper operation of the converter are ensured [14,90].

By upgrading an existing diode-based traction substation to a RTCR-based substation, the energy savings mainly resulting from the braking energy recuperation back to AC grid can be as high as 50%, depending on train speed profile and other parameters specific to the concrete case study. A payback of 2–2.5 years is estimated [14].

By using the same transformer for both thyristor-based bridges, the increasing of the transformer power is estimated to be ~20–30% when compared to a diode rectifier transformer for the similar power. Taking into consideration also the increased number of power semiconductor devices, the additional cost for gaining the ability to recover the braking energy is ~30% [90].

A commercial solution of RTCR is the Enviline Traction Controlled Rectifier (TCR) system of ABB, which includes a four quadrant converter to provide a reverse path for energy flow in the traction substation [50,113]. As specified by ABB, the DC voltage control allows longer distance between substations, reduces losses in rolling stock, and can even prevent interruptions caused by undervoltage. Moreover, the controlled converter can be used in parallel wth the existing diode rectifier. Depending on the nominal traction power supply, three types of Enviline TCR systems are provided by ABB, i.e., for 600/750 V DC, 1500 V DC, and 3000 V DC [113].

An optimal initial firing angle control was proposed for the 12-pulse parallel connected thyristor dual converter located the Hopo commuter subway in Korea, in order to maintain a stable DC voltage. Thus, the slow response and overshoot of DC trolley voltage are eliminated [114].

Another contribution on the topic of bidirectional thyristor-based converters for DC traction is presented by Pejovic et al. [115], where the proposed bidirectional converter consists of a half-bridge thyristor rectifier and a recuperating thyristor bridge instead. Is was experimentally verified on a 10 kW converter, but the concrete application for which such a converter is intended it not specified.

4.4. Reversible Substations with Thyristor-Based Rectifier and PWM Inverter

This solution presented by Cornic in [91] as an outcome of a RailEnergy cooperative research program focused on reduction of energy consumption in transport systems is a system named HESOP (Harmonic and Energy Saving Optimizer). It appeared as a R&D project of Alstom company conducted in partnership with Converteam with the support of ADEME in France. As specified, HESOP is suitable to all known types of DC traction power supply systems, from 600 V DC up to 3000 V DC.

As the prototype scheme in Figure 7 illustrates, the HESOP converter consists of a thyristor-based rectifier in parallel with an IGBT-based inverter. As seen, the traction transformer is preserved and the diode rectifier was replaced by a thyristor-based controlled rectifier.

The controlled rectifier allows maintaining the DC voltage at its nominal value, leading to an increased ability of regeneration. Obviously, the rectifier operates only in the traction regime, during which time the inverter operates as an active power filter. In braking regime, the resulted excess energy is regenerated back to the AC side. Through a dynamic control, the very fast switching between the two regimes is ensured. The main expectations related to the HESOP system were to regenerate over 99% of the retrievable braking energy and to allow for energy savings of ~7% in traction regime [31,91].

Two low power prototypes of 300 kW, 750 V DC were successfully tested in 2009 at the Alstom plant in La Rochelle France [91,116].

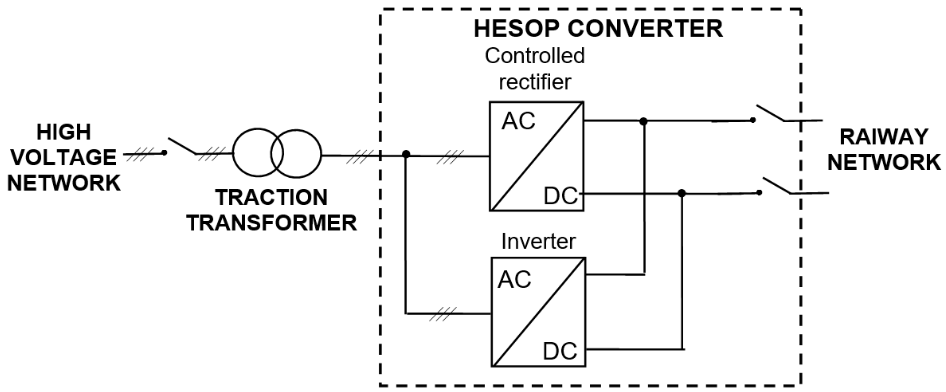

Figure 7. Structure of the prototype Harmonic and Energy Saving Optimizer (HESOP) converter [91].

The original design and validation of the reversible DC substation conceived by ALSTOM to address customer demand for superior energy management capability in public transport was presented at the Railenergy Final Conference in Brussels in November 2010 [116].

The SNCF (French National Railway Company) group proposed new sustainable development approaches in order to improve its energy performance. Among these, there is the solution called "active substation with direct return", which is a structure cast in one piece for traction lines under a power supply voltage of 1500 V DC. It comprises a converter which fulfills the functions of supplying the catenary line and the return of the unused braking energy back into the power grid (Figure 8). Through the control system, new functions are added, such as voltage regulation, harmonics filtering and limitation of the shortcircuit currents. This structure can be used for a new installation or a regeneration of the existing ones [117].

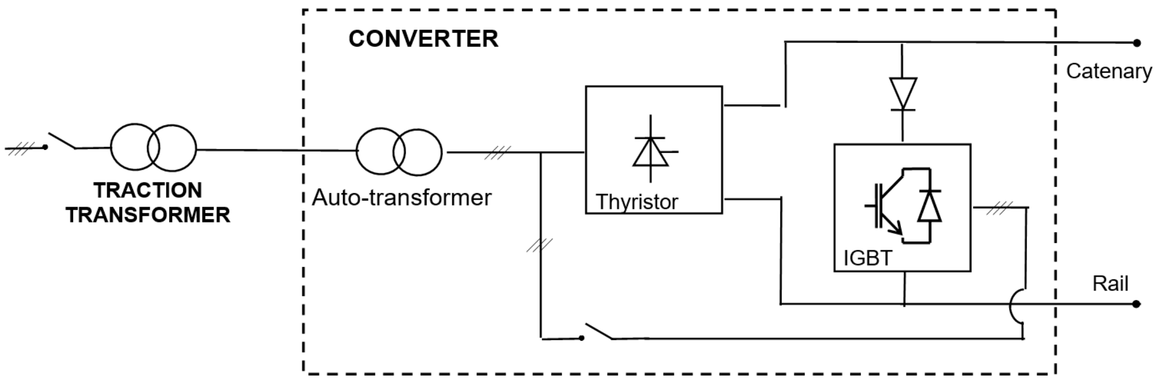

Figure 8. Structure of the active substation with direct return [117].

4.5. Reversible Substations with a Single Rectifier/Inverter Converter

An innovative DC-traction substation provided by Alstom is that of an advanced HESOP system as a reversible substation with a single converter operating as both rectifier and inverter. It is suitable for trams, metro and suburban railways [92].

In 2013, London Underground has chosen to use a separate inverter unit and standalone transformer in parallel with the existing uncontrolled transformer rectifier (Figure 9), as a trial installation on the Victoria Line, due to the clear separation between the traction and recovery equipment [48]. It is about an Alstom's innovative HESOP energy saver, enabling the recovery of more than 99% of the available energy generated during braking [118]. The recovered energy is redistributed into the high voltage network and can be used by station and tunnel equipment [116].

This HESOP 600V 1MW entered into service in March 2015 and is operating as an inverter [92].

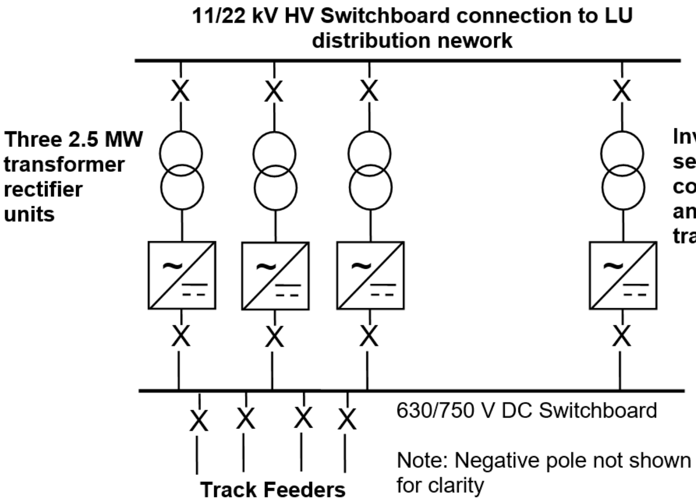

Figure 9. Substation arrangements in upgrading London Underground [48].

A relevant project called RE-USE, and coordinated by Alstom Transport S.A. (France) in partnership with Azienda Trasporti Milanesi Spa(Italy) Alstom Belgium Transport S.A. (Belgium), Alstom Ferroviaria SpA (Italy), was launched in 2013; its main objective is to demonstrate under commercial services conditions the efficiency of the HESOP 1500 V technology to efficiently recover braking energy and reduce energy consumption by at least 15%. As illustrated in Figure 10 and expressed in the Layman's Report 2018, "The HESOP substation includes the following equipment: 1 traction transformer to adapt the incoming voltage; 1 AC filter to smooth the harmonics and control the power factor; 1 converter including an IGBT-controlled rectifier/inverter bridge; 1 DC inductor" [92].

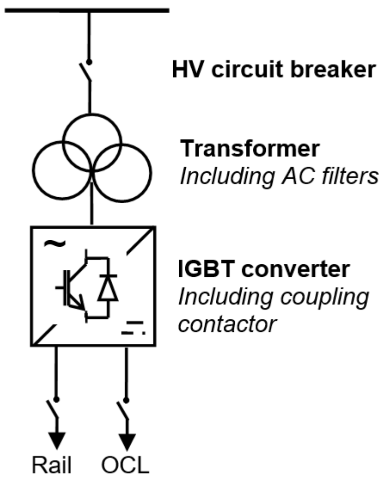

Figure 10. The advanced HESOP architecture [92].

A trial phase under commercial service conditions has been performed from October 2017 to July 2018 in a Milan metro line and the achieved energy savings reached 22% [92].

Other metro and tramway systems where the advanced energy saver HESOP was installed in the last years, since the start of the RE-USE project [92]:

- Sydney Light Rail, Australia, where 13 Hesop (9 Hesop 750V 1.2MW and 4 Hesop 750 V 2 MW) are being tested;
- Panama City metro line, where 8 Hesop 1500 V 4 MW are being implemented;
- Riyadh metro lines, Saudi Arabia, where 70 Hesop 750 V 1.2 MW are being installed; and

- metro lines in Dubai, where 15 Hesop 750 V 2 MW are being implemented for enhancement and extension.

For a typical metro line powered by 1500 V DC, the existing traction power substations have been considered as candidates to be equipped by controlled rectifiers instead of diode rectifiers, through different scenarios for the reversible substations placement in [119]. The simulation-based analysis showed that an optimal choice of the traction substation to be transformed into a reversible substation can lead to an energy efficiency improvement of about 31.5% in the whole metro line.

Finally, Table 3 summarizes the main commercial systems used till now in the implementation of the reversible DC-traction substations.

Table 3. Main commercial solutions for the implementation of reversible DC traction substations.

Commercial Product	Provider	Applications	References
HESOP	Alstom	➢ Paris tramway, 750 V 900 kW, since July 2011 ➢ London Underground, 600 V, 1MW, entered into service in March 2015 ➢ Milan metro line, 1500 V, 4 MW, trial phase under commercial service conditions performed from October 2017 to July 2018 ➢ Sydney Light Rail, Australia, 13 Hesop are being tested (9 Hesop 750 V 1.2 MW and 4 Hesop 750 V 2 MW), in operation since 2017 ➢ Panama City metro, 8 Hesop 1500 V 4 MW are being implemented ➢ Riyadh metro lines in Saudi Arabia, 70 Hesop 750 V 1.2 MW are being installed ➢ Metro lines in Dubai, 15 Hesop 750 V, 2 MW are being implemented ➢ Hamburg, Germany, letter of intent to test Alstom's energy recovery substation, the beginning of 2019	[31,33,48,50,91,92,116,118]
Sitras-TCI	Siemens	➢ Oslo metro, Singapore downtown line, 750 V, 1.5 MW; ➢ Bayerische Zugspitzbahn Bergbahn railway, 1500 V, 2.2 MW	[31,33,50,61,90,93]
INGEBER	INGETEAM Traction	➢ Metro Bilbao, 1500V, 1.5 MW peak power since 2009 ➢ Metro Brussels, Bielefeld light rail network, 750V ➢ Suburban Malaga, 3000 V	[33,47,50,61,90,98,99]
ENVILINE TCR	ABB	➢ 600/750 V, 0.5–5 MW; 1500 V, 0.5–8 MW; 3000V, 1–8 MW	[33,50,113]
Enviline ERS	ABB	➢ Tramway Lódź, 600/750 V, 0.5–1 MW, 2013	[33,50,100]

5. New Trends in Increasing the Energy Efficiency

In the future, the development of new technologies to achieve storage equipment of high performance (high energy capacity, very good charge/discharge rate, and low-size) at competitive prices can relaunch the solution of braking energy storage in both onboard and stationary equipment.

Withal, the implementation of global energy optimization algorithms of traction systems based on new hardware structures with high reliability and acceptable costs can be a direction of increasing energy efficiency over the next decade.

The use of photovoltaic (PV) power generation into traction power supply system, as a clean energy type, has spread as a result of technological developments in the field [120–123].The redundant capacity of the photovoltaic inverter to output reactive power is used in grounding a feed-forward decoupling control strategy for the inverter, in order to reduce the impact of the PV connection to the traction power supply system and improve the power factor of the whole system [121].

In recent years, the application of the smart grid technology to the railway power supply systems is a topical concern to enhance the ecofriendliness of railway transportation in USA, Europe, and Japan, including some experimental tests. For instance, it is considered a future necessity by the East Japan Railway Company [120]. The utilization of regenerated electric power by controlling DC power supply voltage at traction substation is a topical issue.

The integration of the photovoltaic (PV) technology and reversible converters in novel hybrid DC traction power supply systems is an actual concern, as proposed by Zhang et al. [123]. The PV system with a multilevel boost converters can be introduced to reduce the energy cost and increase the reliability of power systems. In this context, advanced control strategies should be designed, to improve the whole performance of the system.

6. Conclusions

Clearly, there is currently a great interest in improving the energy efficiency in urban and suburban DC-traction substations. It is supported by the new achievements in the applied research and commercial equipment of high energetic performance, which covers a wide range of needs for the diversity of older or new DC-traction substations around the world. It is worth mentioning the great number of large-scale partnership projects on this topic and the scientific conferences dedicated to the dissemination of the results.

The main solutions discussed in this review to increase the energy efficiency include power quality conditioning, braking energy storage, and reversible substations. Each application has its own pros and cons and can be implemented in different situations taking into account the particularities of the rail systems.

Although the existence on the market of new equipment provided by reputable large manufacturers is the guarantee of validated solutions, little technical information is published, especially related to the control of these complex systems, that is, the key to the materialization of fundamental research solutions. Through the proposal solutions experimentally confirmed even on small-scale models, significant contributions are being made to the development of knowledge in the field and the identification of new solutions for future implementations.

It is highlighted that the onboard storage systems are preferred as braking energy recovery in light railway systems due to their flexibility and moderate investment cost. Although more costly, the wayside storage systems and reversible substations are the best solution to increase the efficiency of the whole system. Depending on concrete application, the best solution, even a hybrid one, must be selected.

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