الجمهورية الديمقراطية الشعبية الجزائرية

République Algérienne Démocratique et Populaire

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique
Ecole Supérieure des Sciences Appliquées d'Alger

وزارة التعليم العالي والبحث العلمي
المدرسة العليا في العلوم التطبيقية بالجزائر

Département du second cycle

Mémoire de Fin d'Etudes

En vue de l'obtention du diplôme de MASTER

Filière : **Electrotechnique**

Spécialité : **Traction électrique**

Thème :

Regenerative Breaking Energy Recovery

Présenté par :
TOUMINE Ahlem

Encadré (e) par : Dr. BENACHOUR ALI
Co-encadré(e) par : Ing. MEHAL Sofiane

Soutenu publiquement, le :30/06/2022, Devant le Jury composé de :

Dr. Lazhar ROUBACHE :	ESSA-Alger	Président
Dr. AISSIOU Mohamed :	ESSA-Alger	Examinateur
Dr. Ali BENACHOUR :	ESSA-Alger	Encadreur
Ing. Sofiane MEHAL :	COLAS RAIL	Co-Encadreur

Monôme N° : 13/Master / TE/ 2022

Dedication

“

I dedicate my dissertation work to my family and Me.djeroud . A special feeling of gratitude to my loving father and mother, whose words of encouragement and push for tenacity ring in my ears. My sisters Besma , imen,and my niece Loulou,to my two little brothers youcef and younes. I also dedicate this dissertation to my brothers Hamza and Ahmed who have supported me throughout the process. I will always appreciate all they have done.

”

- *Ahlem*

Acknowledgement

“

In the name of Allah, the Most Gracious and the Most Merciful Alhamdulillah, all praises to Allah for the strengths and His blessing in completing this project.

I would like to express my deepest and sincere gratitude to my project Supervisor ***Dr. BENACHOUR Ali*** *. It was great a privilege and honor working studying under your supervision. And many thanks to all personals in* ***Colas rail Algeria*** *consultant office especially my co-supervisor* ***Mr MEHAL Sofiane*** *whom I can't thank enough, without you this work wouldn't have come to light. Thanks ever so much!! Last but not least, I am infinitely grateful to my family members, particularly my parents for their patience, unwavering support, continuous encouragement, and belief in me throughout my whole life. I would have never made it this far without them beside me every step of the way. Finally, a special thanks go to all* ***ESSA-Alger*** *Community.* ***Algiers Higher School of Applied Sciences***

”

ملخص

الهدف من هذه الاطروحة هو دراسة نظام السكة الحديدية الثالثة لمترو الجزائر و كذا امداد كابلات الجهد العالي و الجر باستخدام المعايير و معايير اخرى. أيضا دراسة التخفيف من التآكل الناجم عن ظاهرة التيارات الضالة.

طاقة الكبح التجديدي هي الطاقة التي ينتجها القطار اثناء التباطؤ .عندما يتباطئ القطار ،تعمل المحركات كمولدات و تنتج الكهرباء .يمكن تغذية هذه الطاقة مرة اخرى الى السكك الحديدية الثالثة و استهلاكها من قبل قطارات اخرى تتسارع غى مكان قريب. اذا لم تكن هناك قطارات قريبة ،يتم التخلص من هذه الطاقة كحرارة لتجنب الجهد الزائد . يمكن توفير طاقة الكبح المتجددة عن طريق تركيب انظمة تخزين الطاقة و اعادة استخدامها لاحقا عندما تكون مطلوبة. في هذا البحث ،مختلف الاساليب و التكنولوجيا المقترحة للتجديد تم دراستها و مقارنتها ،هذه الدراسات تشمل: الجدول الزمني للقطار ،انظمة تخزين الطاقة و المحطات الفرعية القابلة للعكس.

الكلمات المفتاحية: الطاقة المتجددة ، PWM ، محطة فرعية عكسية

Abstract

regenerative braking energy is the energy produced by a train during deceleration. When a train decelerates, the motors act as generators and produce electricity. This energy can be fed back to the third rail and consumed by other trains accelerating nearby. If there are no nearby trains, this energy is dumped as heat to avoid over voltage. Regenerative braking energy can be saved by installing energy storage systems (ESS) and reused later when it is needed. In this comprehensive paper, the various methods and technologies that were proposed for regenerative energy recuperation have been analyzed, investigated, and compared. These technologies include: train timetable optimization, energy storage systems (onboard and wayside), and reversible substations.

Keywords : Regenerative energy , PWM, reversible substation

Résumé

l'énergie de freinage régénératif est l'énergie produite par un train pendant la décélération. Lorsqu'un train décélère, le moteurs agissent comme génératrices et produisent de l'électricité. Cette énergie peut être renvoyée au troisième rail et consommée par d'autres trains accélèrent à proximité. S'il n'y a pas de trains à proximité, cette énergie est déversée sous forme de chaleur pour éviter la surtension. L'énergie de freinage régénératif peut être économisée en installant des systèmes de stockage d'énergie et réutilisée plus tard lorsqu'elle est nécessaire. Dans ce document , les diverses méthodes et technologies qui ont été proposées pour la régénération et la récupération de l'énergie a été analysée, étudiée et comparée. Ces technologies sont : optimisation, systèmes de stockage d'énergie et sous-stations réversibles.

Mots clés : Regénération d'energie ,PWM , station reversible

Contents

List of Figures

List of Tables

Liste des sigles et acronymes

ESS	*Energy Storage System*
BESS	*Battery Energy Storage System*
SCESS	*Super Capacitor Energy Storage System*
TCI	*Thyristor line Commutated Inverter*
PWM	*Pulse Width Modulation*
RTCR	*Reversible Thyristor Controlled Rectifier*
HESOP	*Harmonic and Energy Saving Optimizer*
TCR	*Thyristor Controlled Rectifier*

Chapter 1

Introduction

Energy efficiency and reducing energy consumption are important challenges in electric rail transit systems. Studies show that up to 40%of the energy supplied to a train can be fed back to the third rail through regenerative braking . Since 1970, electric vehicles with regenerative braking energy capability have been developed .In regenerative braking, which is common in today's electric rail systems, a train decelerates by reversing the operation of its motors. During braking, the motors of a train act as generators converting mechanical energy to electrical energy.

This energy can be fed back to the third rail, and absorbed by other nearby accelerating trains. If there are no other neighboring trains, this energy is dumped to a resistor.
Nowadays, the energy-saving technology for urban rail transportation is mainly focused on how to carry out the regeneration braking energy recycling. A variety of methods have been proposed, such as the use of inverter technology and the use of various energy storage devices.
The goal of this paper is to provide a comprehensive review of regenerative braking energy. Various solutions and technologies have been described and discussed. Advantages and disadvantages of each solution have been presented.

This paper is organized as follows:
In section II, a discussion on system integration is presented, including the common topologies of rectifier substations. In section III, the energy dissipation by risistors is discussed. In section IV, the train timetable is presented .In section V, utilization of energy storage systems for regenerative energy recuperation in electric transit systems is discussed. . In section VI, mainly focuses on various reversible substation systems . Section VIII is about A comparison between different recuperation techniques. Finally, some of the conclusions that can be derived are summarized in section IX.

Chapter 2

Regenerative Energy Utilization

2.1 System Integration

Electric rail transit systems consist of a network of rails, supplied by geographically distributed power supply substations. A typical DC transit substation consists of a voltage transformation stage that steps down medium voltage to a lower voltage level, followed by an AC/DC rectification stage that provides DC power to the third rail. There are also traction network protection devices (circuit breaker, insulator, etc.) both at the AC and DC sides to prevent personnel injuries and equipment damage. On the DC side, rectifiers have overcurrent, reverse current trip protection and high speed breaker. There are impedance relays along the track or on the vehicle to protect earth faults. Figure 2.1 shows an example of a substation in which two transformers and two rectifiers are connected in parallel, to increase the power supply reliability. Auxiliary loads, such as elevators, escalator, ventilation systems and lighting systems are supplied through a separate transformer.[1]

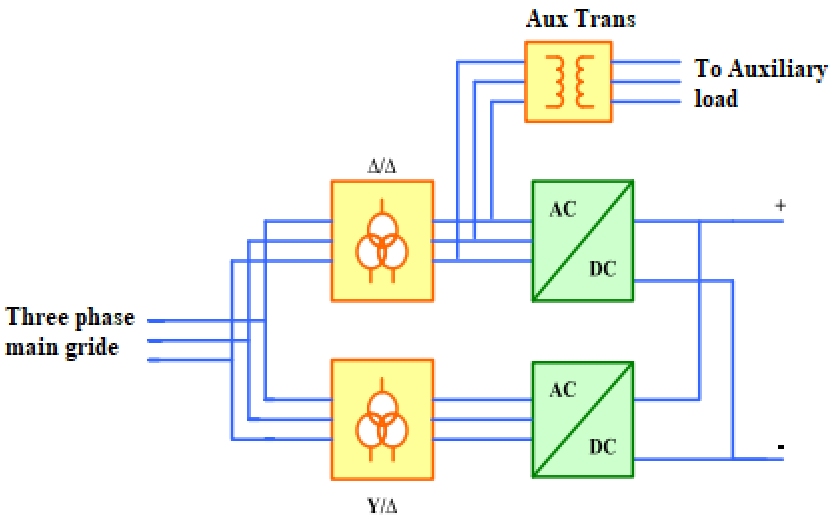

Figure 2.1: A schematic diagram of a typical power supply substation.

2.2 Energy Dissipation

The resistor dissipation device has simple electrical principle, high reliability and small maintenance workload, thus obtains a lot of mature experience of being used onboard and on the ground. However, the resistor dissipation device will convert the braking energy into heat energy, which is conducted into the air, leading to the tunnel temperature rise(figure 2.2). So additional ventilation devices inside the substation are required, increasing the design difficulty and cost of substation, and causing a waste of energy.[2]

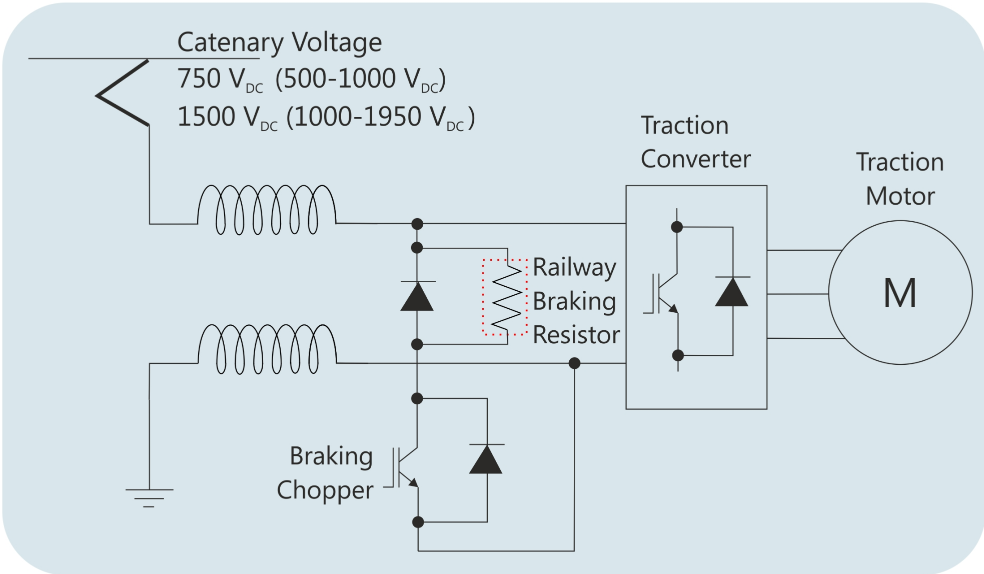

Figure 2.2: The regenerative energy absorption device of ground braking resistor type.

2.3 Train Timetable Optimization

Train timetable optimization has been proposed as one of the approaches to maximize the reuse of regenerative braking energy. In this method, the braking and acceleration actions of two neighboring trains are scheduled to occur simultaneously; therefore, some of the energy produced by the decelerating train is used by an accelerating one. Some studies show that up to 14% of energy saving can be achieved through timetable optimization.[1]

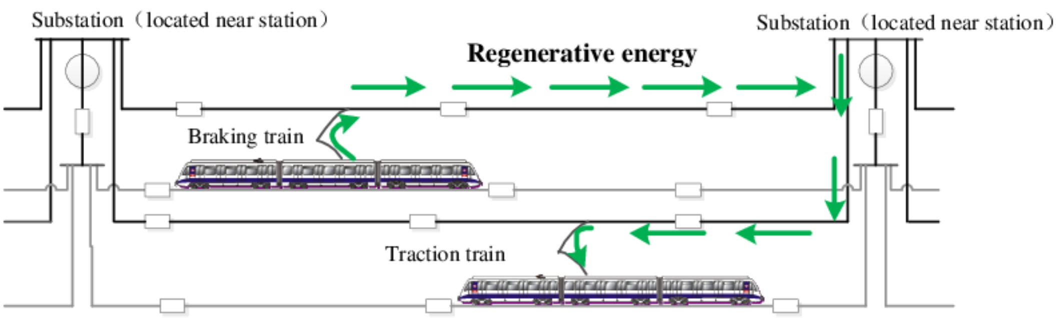

Figure 2.3: Immediate-energy-exchange-between-trains-by-regenerative-braking.

2.4 Regenerative Breaking Energy

At present, the way of regenerative braking energy utilization in urban rail transit is divided into two basic types, including the energy storage and energy feedback type.

2.5 Energy Storage

An energy storage system, if properly designed, can capture the energy produced by a braking train and discharge it when needed. Consequently, the amount of energy consumed from the main grid is reduced. In addition, using ESS can reduce the peak power demand, which not only benefits the rail transit system but also the power utility. ESS may be used to provide services to the main grid, such as peak shaving. ESS can be implemented in two different ways: onboard and wayside. In onboard, ESS is mostly located on the roof of each train. On the other hand, wayside ESS is located outside the train, on the trackside. It can absorb the regenerative energy produced by all trains braking within the same section and deliver it later to other trains accelerating nearby.[1] Existing implementations of ESSs for heavy rail systems use three energy storage technologies: batteries, super capacitors, and flywheels. The fourth technology— superconducting magnetic energy storage—is still in the experimental stage.[3] Several important factors must be considered while designing an ESS, and choosing the most suitable storage technology. These factors include: the energy capacity and specific energy, rate of charge and discharge, durability and life cycle.[1]

2.5.1 Batteries

Battery is the oldest electric energy storage technology, which is widely used in different applications. A battery consists of multiple electrochemical cells, connected in parallel and series to form a unit. Cells consist of two electrodes (i.e. anode and cathode) immersed in an electrolyte solution. Batteries work based on the following principle: due to reversible chemical reactions (i.e. oxidation and reduction) that occur at the electrodes, a potential difference appears between them (voltage between the anode and the cathode). Consequently, energy can reversibly change from the electrical form to the chemical form .[1] The advantage of battery energy storage technology is that the battery itself has large energy density, which is out of reach for other energy storage components. It is very appropriate to use the battery energy storage system in places where a large amount of energy reserve is needed. But the small power density, short life and difficulty in dealing with wasted batteries are weaknesses which limit the further development of battery storage technology.[2] There are different types of batteries, the most common ones are lead-acid, nickel–metal hydride (Ni-MH), and lithium-ion (Li-ion).[3]

As early as the 1990s, the German Berlin subway applied the battery energy storage technology in the line . Toshiba in Japan developed the traction energy storage system (TESS) with lithium titanate battery modules for DC railway systems, which have functions including absorption of regenerative braking energy, peak clipping, prevention of sharp voltage drop, supplying power to the trains on the line when power fault occurs, et al. The system has been used in Japan Tobu railway lines, as shown in figure 2.4 .[2]

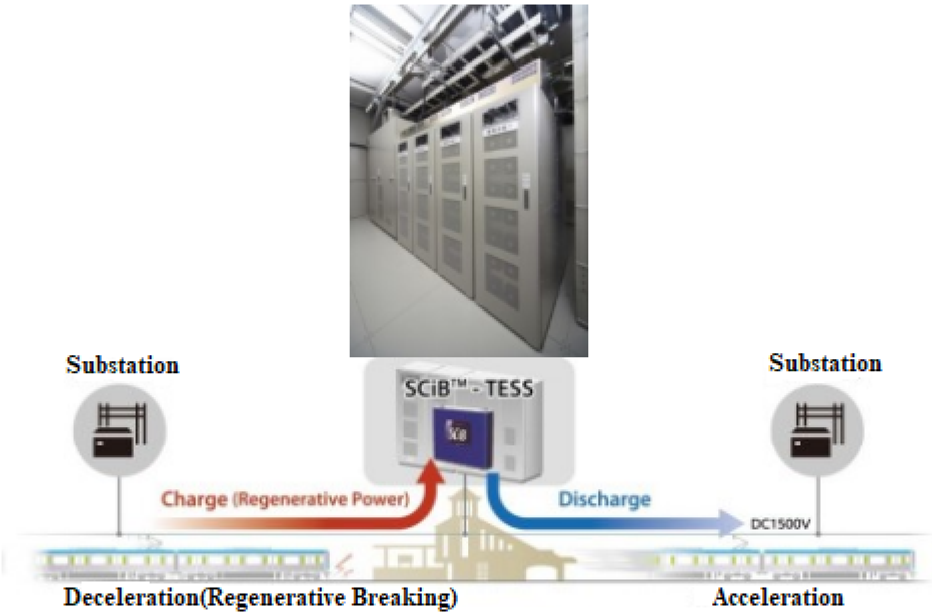

Figure 2.4: Toshiba's TESS system.

2.5.2 flywheel

The main principle of the flywheel energy storage technology is to convert the electric energy generated by train braking into the kinetic energy of the high-speed rotating flywheel, i.e. when the train generates the braking energy, the flywheel speeds up and the energy is stored in the form of kinetic energy; when the traction energy is needed, the flywheel slows down, and the stored energy is released to the traction network, as shown in figure 2.5

Some of the advantages of flywheel ESS are high energy efficiency (95%), high power density (5000 W/kg) and high energy density (50 Wh/kg), less maintenance, high cycling capacity (more than 20000 cycles) and low environmental concerns . Flywheel systems present some drawbacks, such as very high self-discharge current, risk of explosion in case of failure, high weight and cost. However, system safety is believed to be improvable through predictive designs, and smart protection schemes. According to some publications, if/when the cost of flywheel systems is lowered; they can be extensively used in all industries and play a significant role in the worldwide energy sustainability plans. Based on the simulation results presented in , flywheel ESS is capable of achieving 31% energy saving in light rail transit systems.[1]

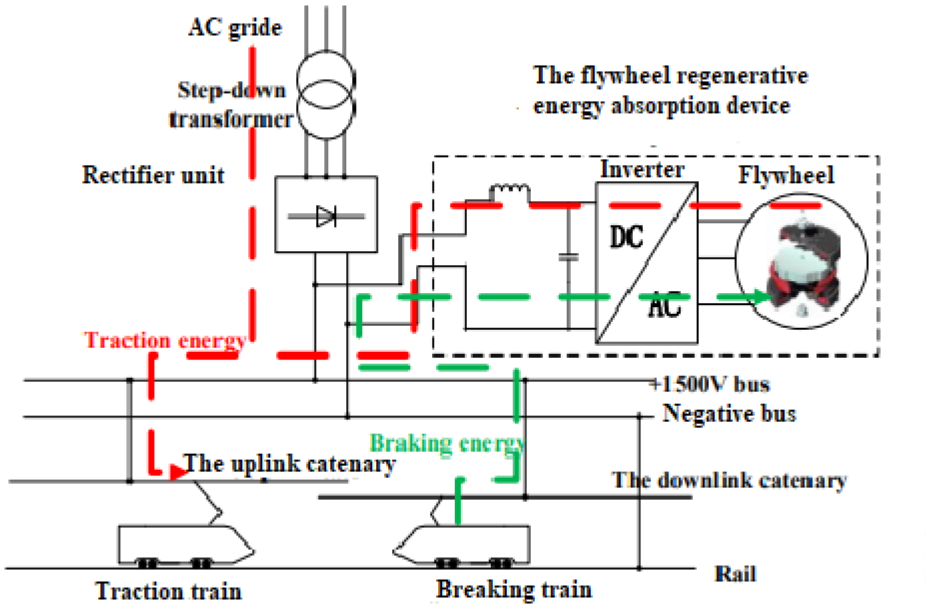

Figure 2.5: The regenerative energy storage device of flywheel type.

2.5.3 Super Capacitors

Among the energy storage technologies applied to urban transportation systems, during the recent years, a great spread and focus has been aimed to super capacitors (SC). They exhibit energy densities (6 Wh/kg) lower than those of batteries and flywheels but higher power densities (6 kW/kg), with discharge times ranging from ten of seconds to minutes.These characteristics suggest thier utilization for improving the dynamic performance and energy efficiency of the system .[4]

Super capacitor is a type of electrochemical capacitors consisting of two porous electrodes immersed in an electrolyte solution. By applying voltage across the two electrodes, the electrolyte solution is polarized. Consequently, two thin layers of capacitive storage are created near each electrode. There is no chemical reaction, and the energy is stored electrostatically. Because of the porous electrode structure, the overall surface area of the electrode is considerably large. Therefore, the capacitance per unit volume of this type of capacitor is greater than the conventional capacitors.[1]

The electrical characteristics of super capacitors highly depend on the selection of the electrolyte and electrode materials. However the maximum operating voltage of ultracapacitors is very low and they suffer from high leakage current. Because of these two drawbacks, they cannot hold energy for a long time . Recently, Li-ion capacitors have been developed with less leakage current and higher energy and power densities than batteries and standard super capacitors.[1]

2.5.4 Comparison of typical energy storage devices.

The table bellow (Table 2.1) presente the Comparison of typical energy storage devices.

Table 2.1: Comparison of typical energy storage devices

Types	Energy density (Wh/kg)	Power density (W/kg)	Efficiency	Cycling life (number of cycles)	Cost ($/kWh)	Cost ($/kW)
Lead-acid battery	20–50	25–300	70–90	200-2000	50–400	300–600
nickel-cadmium battery	30–75	50–300	60-80	1500-3000	400–2400	500–1500
nickel-metal hydride battery	60-80	200-250	65-70	1500-3000	400–2400	–
Lithium ion battery	75–200	100–350	90-100	1000–10,000	500–2500	1200–4000
Lithium polymer battery	100–200	150–350	90-100	600–1500	900–1300	–
supercapacitor	2.5–15	500–5000	90–100	<106	300–2000	100–300
flywheel	5-100	1000-5000	90-95	<107	1000–5000	250–350
Superconducting magnetic energy storage system	0.5–5	500–2000	95–100	>100,000	1000-10,000	200–300

2.5.5 Onboard Energy Storage

In onboard ESS, the storage medium is placed on the vehicle. It can be placed on the roof or under the floor of the vehicle. Placing ESS under the floor is relatively costly, because space is not readily available. A schematic overview of onboard ESS is shown in Figure 2.6. The efficiency of onboard ESS is highly dependent on the characteristic of the vehicle, which can directly affect the amount of energy produced and consumed during braking and acceleration, respectively . Other advantages of onboard energy storage are peak power reduction, voltage stabilization, catenary free operation and loss reduction . On the other hand, the cost of implementation, maintenance, and safety concerns, are high because unlike wayside storage, in onboard ESS, an ESS is needed for each train.[1] Onboard ESS is already in use by some rail transit agencies. In addition, several agencies all around the world are considering –or actually testing- it. Various technologies have been used for onboard ESS; among them, super capacitors have been more widely implemented in many transit systems. Due to safety and cost limitations, onboard flywheels did not acquire much attention, and still need more investigation.
[1]. The advantage of the onboard energy storage type is that the regenerative braking energy of the train can be stored in time, reducing the loss caused by the energy flow between the lines. On the other hand, when the train starts, it can quickly enter the discharge state according to the train state, thus reducing the DC grid voltage drop at the pantograph . However, the onboard energy storage device also increases the vehicle weight, occupies the body space, and leads to increase of traction energy consumption.[2]

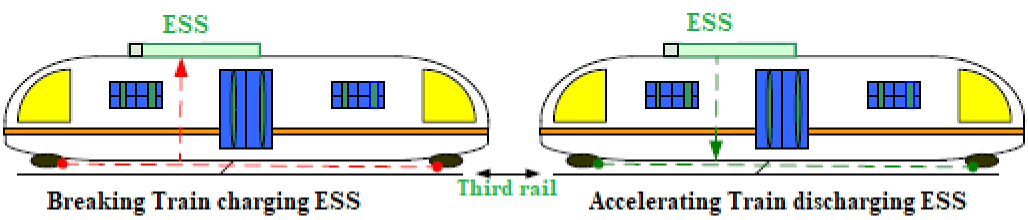

Figure 2.6: Onboard energy storage systems.

2.5.6 Wayside Energy Storage

A schematic overview of wayside ESS is shown in Figure 2.7. The main concept of wayside ESS is to temporarily absorb the energy regenerated during train braking and deliver it back to the third rail when needed. Generally, it consists of a storage medium connected to the third rail through a power control unit. In addition to the general advantages that were previously mentioned for energy storage systems, wayside ESS can also help minimize problems related to voltage sag . Voltage sag, which is temporary voltage reduction below a certain limit for a short period of time, can damage electronic equipment in a rail car, and affect the performance of trains during acceleration. ESS can be designed to discharge very fast, and by injecting power to the third rail, they help regulate its voltage level. In addition to the economic benefits provided by ESS through recapturing braking energy, ESS can be designed to participate in the local electricity markets as a distributed energy resource . Some other applications that can be provided by wayside ESS include peak shaving, load shifting, emergency backup and frequency regulation.[1]

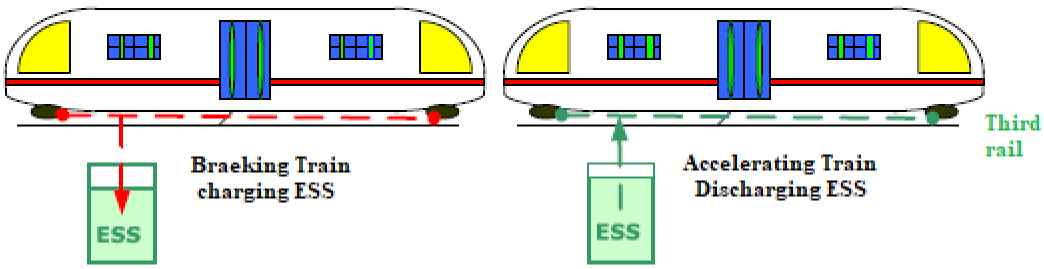

Figure 2.7: Wayside energy storage systems.

2.6 Reversible Substation

Another approach to reuse regenerative braking energy is through the use of reversible substations, as shown in Figure 2.8. A reversible substation, also known as bidirectional or inverting substation, provides a path through an inverter for regenerative braking energy to feed back to the upstream AC grid, to be consumed by other electric AC equipment in the substation, such as escalators, lighting systems, etc. This energy can also feed back to the main grid based on the legislation and rules of the electricity distribution network. Reversible substations must maintain an acceptable power quality level for the power fed back to the grid by minimizing the harmonics level Even though reversible substations are designed to have the ability to feed regenerative braking energy back to the upstream network, if maximum regenerative energy recuperation is targeted, priority should be given to the energy exchange between trains on the DC side of the power network.[1]

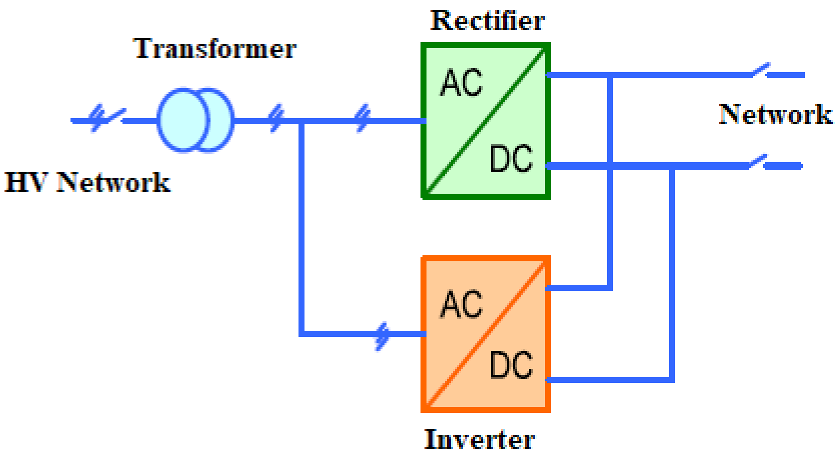

Figure 2.8: Block diagram of a reversible substation.

2.6.1 Objectives of Reversible Substations

The key benefits expected from reversible dc traction substations are[5]:

- Regeneration of 99% of the braking energy at all time, while maintaining priority to natural exchange of energy between trains, this will allow eliminating the braking resistors, and thus reduce the train mass and heat release.
- Regulation of its output voltage in traction and regeneration modes to reduce losses, and increase the pick-up of energy from distant trains.
- Reducing the level of harmonics and improvement of the power factor on the ac side.

2.6.2 Reversible Substations Systems

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

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 2.9 . 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. As shown in Figure 2.9, the components of the TCI are included in a panel group to be easily integrated into existing substations.
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.[6]

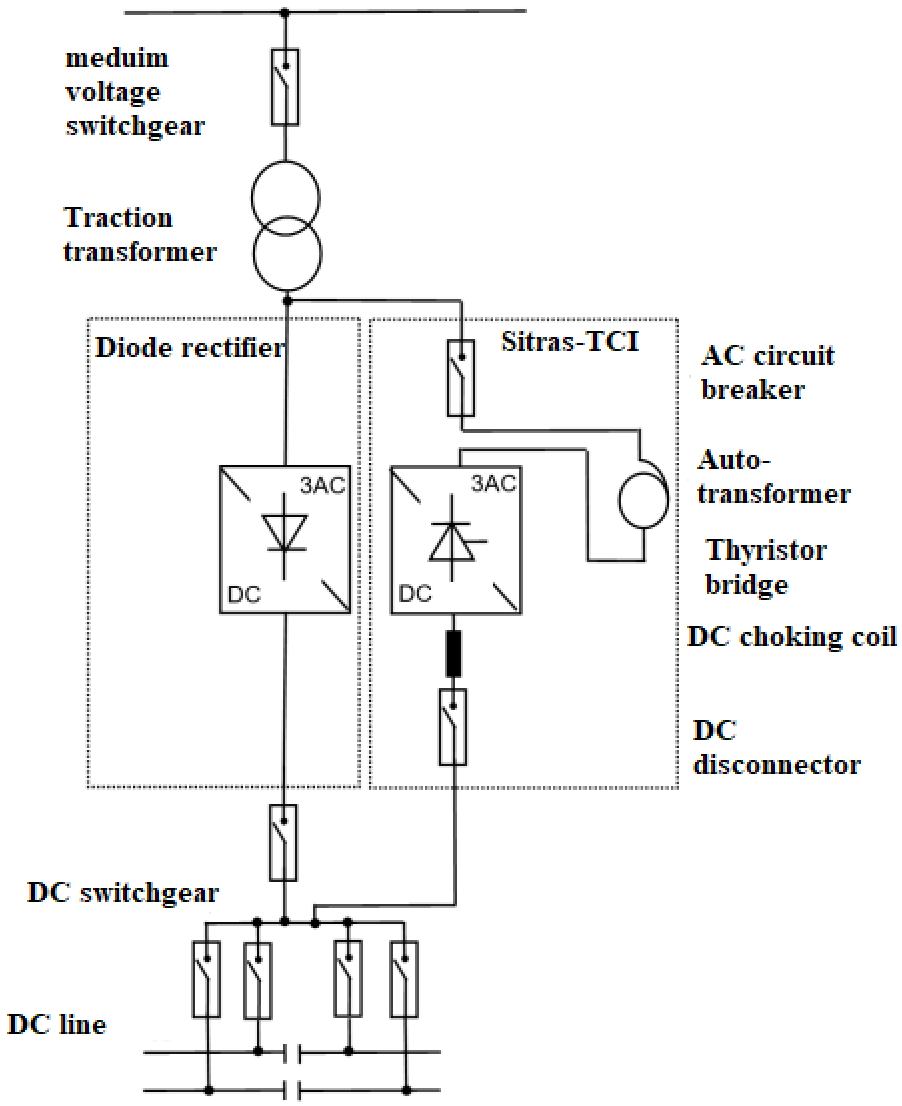

Figure 2.9: chematic diagram of the Sitras TCI integrated into an existing DC-traction substation with uncontrolled rectifier

Reversible Substations with Diode Rectifier and PWM Inverter

A diode rectifier can also be combined with a PWM converter to provide a reverse path for the energy. PWM converters have the advantage of working at unity power factor, and the disadvantage of high cost and high switching losses. In order to use PWM converters for reversible substation purposes, a step up DC/DC converter should be added between the PWM converter and the DC bus. In addition, to reduce the harmonics level and avoid current circulation, a DC filter needs to be added at the output of the converter.[1]
The use of a boost DC/DC converter was adopted in the commercial solution called INGEBER conceived and developed by INGETEAM Traction.

As illustrated in Figure 2.10, 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. 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. 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.[6]

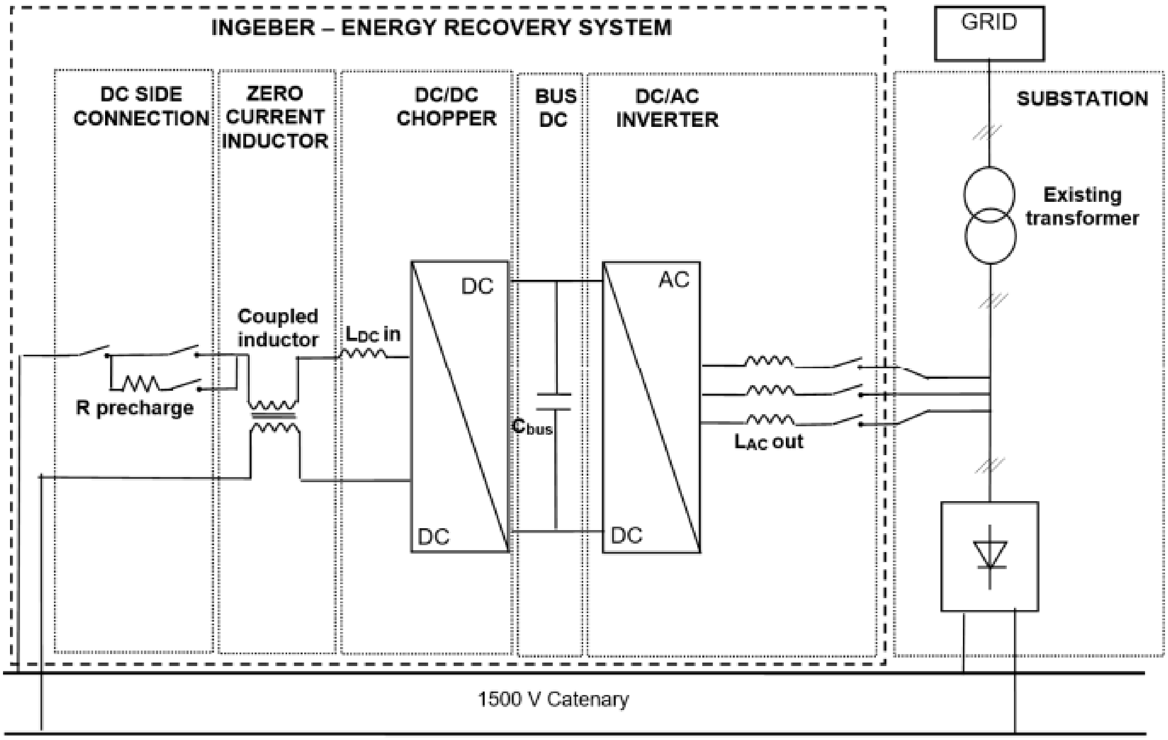

Figure 2.10: Schematic diagram of the INGEBER system integrated into an existing DC-traction.

Reversible Substations with Reversible Thyristor Controlled Rectifiers

the RTCR consists of two TCRs, which are connected in parallel, providing a path for the energy in forward and reverse directions. Only one of these TCRs can be fired at a time therefore, no current will circulate between them, and there will be no need for a DC inductor. When RTCR is working in the forward direction (AC/DC), the inverter acts as an active filter.[1]

In this approach, the diode rectifiers need to be replaced with RTCRs and the rectifier transformers need to be changed, which makes this approach more expensive and complex . However, RTCRs have advantages, such as voltage regulation and fault current limitation.[1]

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.[6]

Reversible Substations with Thyristor-Based Rectifier and PWM Inverter

Is an anti-parallel thyristor controlled rectifier (TCR) connected backward to provide a path for transferring energy from the DC side to the AC one. This technology has been used in an Alstom reversible substation setup called HESOP (Harmonic and Energy Saving Optimizer).[1]
Hesop is an advanced reversible power substation which both supplies traction voltage to a network and recovers braking energy from vehicles. It can be retrofitted to existing systems or built into new networks in construction phase(figure 2.11) .[7]
Its dynamic voltage regulation adapts the power supply to the network's requirements; this means that if traffic increases, power can be scaled up without changing infrastructure. But Hesop also captures more than 99% of recoverable braking energy, reinjecting it into the power grid for resale or reusing it in station facilities such as escalators, lighting and ventilation.[7]

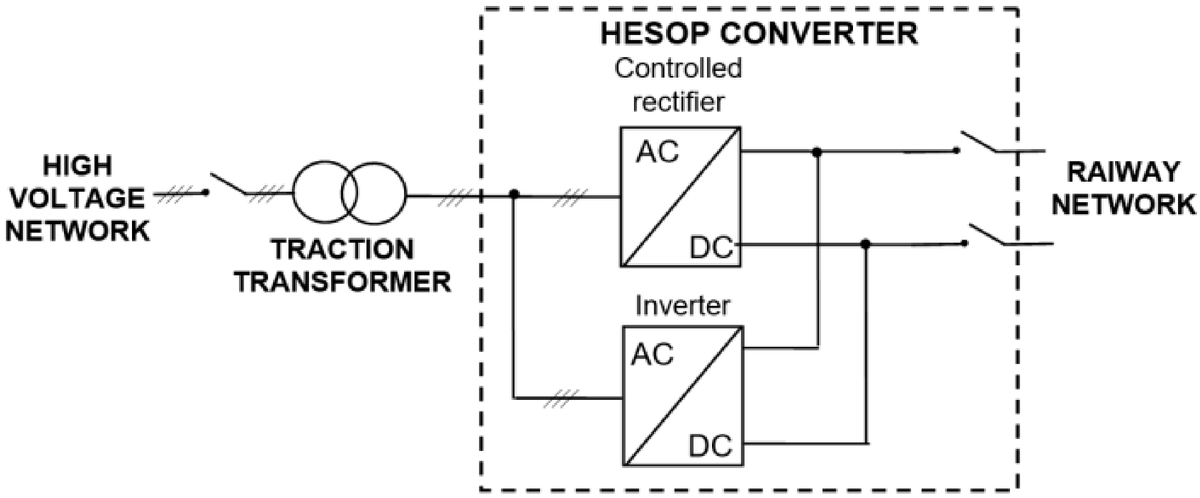

Figure 2.11: Structure of the prototype Harmonic and Energy Saving Optimizer (HESOP) conver.

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. In 2013, London Underground has chosen to use a separate inverter unit and standalone transformer in parallel with the existing uncontrolled transformer rectifier (Figure 2.12), as a trial installation on the Victoria Line, due to the clear separation between the traction and recovery equipment . It is about an Alstom's innovative HESOP energy saver, enabling the recovery of more than 99% of the available energy generated during braking.The recovered energy is redistributed into the high voltage network and can be used by station and tunnel equipment.[6]

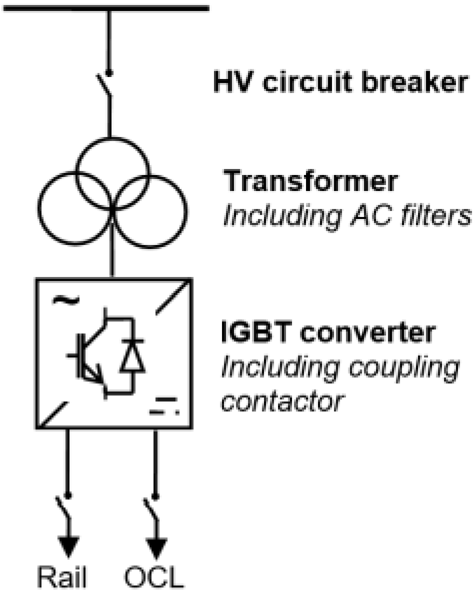

Figure 2.12: The advanced HESOP architecture.

2.7 Comparison of Regerenative Energy Absorption Devices

Through the above analysis of research and application of various kinds of regenerative braking energy processing, a comparison of a various approaches is shown in table 2.2 is of certain value and reference.

Table 2.2: Comparison of regerenative energy absorption devices[1]

	The resistor dissipation type	The energy feedback type	The energy storage type		
			Battery	Flywheel	Supercapacitor
Energy saving effect	bad	good	relatively good	relatively good	relatively good
Voltage stabilization effect	unidirectional voltage stabilization	unidirectional voltage stabilization	bidirectional voltage stabilization	bidirectional voltage stabilization	bidirectional voltage stabilization
Relationship with the AC grid	no	Causing harmonics	no	no	no
Service life	long	relatively long	short	relatively long	relatively long
Service cost	low	relatively high	relatively high	high	relatively high
Energy density	—	—	high	relatively high	low
Power density	—	—	low	relatively high	high
Matching with urban rail transit	—	—	relatively bad	relatively good	relatively good

Chapter 3

Conclusion

In this work, a comprehensive review on different methods and technologies the can be used for regenerative braking energy recovery has been presented. Three main solutions have been used worldwide including train timetable optimization, energy storage system, and reversible substations. Each application has its own pros and cons and can be implemented in different rail systems with different characteristics. Train timetable optimization is a solution with low cost, which typically requires no new installations. The main purpose of this method is to synchronize the accelerating and decelerating phases of trains in order to increase the natural exchange of regenerative braking energy among them.

However, application of this technique might be limited by certain service requirements. It requires supervisory real-time monitoring and control of the trains, which may not be available in some systems.

Another solution for regenerative energy recovery is through the use of energy storage systems. In this method, regenerative braking energy that is produced by trains is stored in onboard or wayside energy storage system, and released later on when it is needed. Beside energy savings, both types of ESS can reduce peak power demand and improve the third rail voltage level.

According to some publications, about 30% of the energy consumed by the train can be saved using ESS. The location, size and type of storage technology used for ESS significantly impact the amount of regenerative energy that can be recuperated. In addition, the various types of technologies that are available for storing regenerative braking energy have been reviewed in this paper. Super capacitors, batteries and flywheels are commonly used technologies. Among them, super capacitor has been used widely all over the world mostly because of its characteristics, such as fast response, high power density and long life cycle. In case of battery, Li-Ion battery is the most utilized one because of its high number of cycles, low weight, small size and commercial availability. A combination of these technologies seems to be a good option, but still needs further investigation.

Reversible substation is another way to increase the amount of energy that can be saved during vehicle braking. In this method, a reverse path is provided through an inverter for energy to flow back to the main grid. Implementing this method depends on the regulations of feeding power back to the main grid. There are two common methods to provide a revers path: a) combination of a diode rectifier with an inverter, b) using reversible thyristor-controlled rectifier (RTCR). There are commercially available reversible substations that are under test in several locations globally. When using reversible substation, priority should be given to the natural energy exchange between vehicles, and then, the surplus of energy can fed back to the main grid. Studies show that up to 13the consumed energy by a vehicle can feed back to the main grid using this method.

Bibliography

[1] M. Khodaparastan, A. A. Mohamed, and W. Brandauer, "Recuperation of regenerative braking energy in electric rail transit systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 8, pp. 2831–2847, 2019, Publisher: IEEE.

[2] Y. Lu, Y. Zhao, X. Zhao, G. Li, and C. Zhang, "Status analysis of regenerative braking energy utilization equipments in urban rail transit," in *2017 IEEE transportation electrification conference and expo, Asia-Pacific (ITEC Asia-Pacific)*, IEEE, 2017, pp. 1–6.

[3] V. Gelman, "Energy storage that may be too good to be true: Comparison between wayside storage and reversible thyristor controlled rectifiers for heavy rail," *IEEE Vehicular Technology Magazine*, vol. 8, no. 4, pp. 70–80, 2013, Publisher: IEEE.

[4] F. Ciccarelli and D. Iannuzzi, "A Novel energy management control of wayside Li-Ion capacitors-based energy storage for urban mass transit systems," in *International symposium on power electronics power electronics, electrical drives, automation and motion*, IEEE, 2012, pp. 773–779.

[5] D. Cornic, "Efficient recovery of braking energy through a reversible dc substation," in *Electrical systems for aircraft, railway and ship propulsion*, IEEE, 2010, pp. 1–9.

[6] M. Popescu and A. Bitoleanu, "A review of the energy efficiency improvement in DC railway systems," *Energies*, vol. 12, no. 6, p. 1092, 2019, Publisher: MDPI.

Webographie

[7] *Hesop: Saving energy and costs in a single solution*, en. [Online]. Available: https://www.alstom.com/solutions/infrastructure/hesop-saving-energy-and-costs-single-solution (visited on 06/18/2022).