Overview of energy efficiency in urban electric railways

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ABSTRAK

Dunia sedang bergerak menuju produksi nol CO2 dan membatasi kenaikan suhu global hingga 1,5°C pada tahun 2050 dengan mengurangi penggunaan bahan bakar fosil sebagai sumber energi yang tidak berkelanjutan. Sebagai transisi dari pengurangan ini, energi listrik telah menjadi sumber energi utama di sektor industri, transportasi, konstruksi, dan sektor lainnya. Di sektor transportasi, kereta listrik perkotaan telah menjadi mode transportasi pilihan oleh masyarakat di seluruh dunia karena standar keselamatan yang tinggi dan pelayanan yang unggul dibandingkan dengan transportasi darat lainnya. Namun, kereta listrik memerlukan jumlah energi yang signifikan untuk beroperasi, sehingga diperlukan upaya untuk mengoptimalkan penggunaan listrik secara keseluruhan. Makalah ini menyajikan kajian literatur terkait efisiensi energi listrik dalam bidang kereta listrik perkotaan, dengan menggunakan metode pengendalian kereta dan pemanfaatan sistem pengereman regeneratif sebagai strategi pemulihan energi yang paling efisien.
Kata Kunci: Railway, Efficiency Energy, Regenerative Braking, Train Control

ABSTRACT

The world is moving towards zero CO2 production and limiting the global temperature increase to 1.5°C by 2050 by reducing the use of fossil fuels as an unsustainable energy source. As a transition from this reduction, electric energy has become the primary energy source in the industrial, transportation, construction, and other sectors. In the transportation sector, urban electric trains have become a preferred mode of transportation by people worldwide due to their high safety and service levels compared to other land transportation. However, electric trains require a significant amount of energy to operate, so efforts are needed to optimize total electricity usage. This paper provides a literature study related to electric energy efficiency in the field of urban electric trains, using train control methods and the utilization of regenerative braking systems as the most efficient energy recovery strategy.
Keywords: Railway, Efficiency Energy, Regenerative Braking, Train Control

1 INTRODUCTION

Based on the International Energy Agency's (IEA) 2021 report titled "A Road Map for the Global Energy Sector," the current trajectory of the world is directed towards the attainment of carbon neutrality as well as the constraint of global temperature escalation to a maximum of 1.5°C by 2050. In 2015, the IEA, consisting of 22 advanced countries and energy leaders worldwide, made a full commitment to reduce the use of fossil fuels as non-renewable energy sources. As a transition from this reduction, electric energy has become the primary source of energy in various sectors including industry, transportation, construction, and others. By 2030, the percentage of electric cars sold globally is expected to exceed 60%[1].

In recent years, urban electric train transportation has become the preferred mode of transportation for people due to its mass-based transportation services and higher level of service compared to other land-based transportation options. Moreover, urban electric trains are more environmentally friendly as they do not emit CO2 pollution, which significantly contributes to global warming. However, despite being environmentally friendly, urban electric trains require a substantial amount of electrical energy for their operation. Therefore, efforts need to be made to conserve energy in their operations.

The use of train control and regenerative braking technologies on urban electric trains is one well-liked strategy for lowering energy usage. Train control on electric trains can be used to save energy by optimizing the train's speed at every point in time during the journey. Train control is designed to achieve optimal

speed at every part of the track, taking into account factors such as the track's topography, passenger load, and weather conditions. In the operation of electric trains, the use of train control can help improve energy efficiency and reduce operational costs. Meanwhile, Vehicles with regenerative braking systems may utilize the kinetic energy created during braking to generate electrical energy that can be stored and used again as a power source. In electric trains, when the brakes are applied, the electric motor that usually functions as a drive motor will change function and become a generator, which will convert kinetic energy into electrical energy. This electrical energy is then stored in a battery or capacitor and can be reused to power the electric motor when the train is moving or when acceleration is needed. Therefore, energy consumption on electric trains can be reduced.

This paper focuses on energy efficiency using train control methods and the utilization of regenerative braking systems. Currently, many researchers are studying energy efficiency in the field of railways, especially urban electric trains. P. G. Howlett and A. Albrecht developed the best control techniques after simulating the dynamics of train movement with mathematical models to reduce travel time and increase energy efficiency [2]–[5]. The suggested control techniques include adjusting the train's speed and acceleration, limiting its speed when negotiating curves, and regulating its spacing. V. De Martinis and M. Gallo offer a variety of models and techniques, such as control theory approaches and numerical optimization, to improve train control. Model predictive control, optimum control, and adaptive control are some of the suggested control strategies. In the meanwhile, conjugate gradient methods, quasi-Newton methods, and genetic algorithms are utilized as optimization techniques. According to the findings, depending on train operating circumstances, the energy recovery system can increase energy efficiency by 25% to 30% [6].

S. Yang created a train departure schedule optimization model for a metro system that uses less energy. The model has two key goals: best passenger allocation to trains and best energy allocation to energy-efficient trains. By using "bi-objective optimization," which is a type of optimization technique, the model looks for the best solutions to two optimization problems at once. This study showed a 20.09% increase in the amount of energy produced by the regenerative brake system and a reduction of up to 3717 hours in the overall amount of passenger journey time [7]. A. Rupp analyzed the flywheel energy storage device used in light rail transportation from a technical and economic perspective. To assess the efficacy of the flywheel

energy storage system relative to conventional battery systems, the methodology employed in this study entailed the development of a model for the flywheel energy storage system through the utilization of Matlab/Simulink software and subsequent simulation of the model. It was determined that compared to traditional battery systems, the flywheel energy storage system offers benefits in terms of energy storage capacity, longer service life, and the capability to manage bigger electric loads. 31% of energy usage may be reduced by using a flywheel [8]. To save energy in the metro system, S. Ahmadi provide a technique for maximizing the usage of stationary energy storage devices and train control. A mathematical model used in the suggested strategy takes into account things like trip duration, train load, and energy recovery system consumption. The utilization of stationary energy storage devices and railway train control are optimized concurrently. Depending on train operating circumstances, the results demonstrate that using the technology can cut energy usage by up to 18% [9].

This article presents an exhaustive literature review on train control and the application of regenerative braking system, spanning from the 1960s until recent times. The approach employed in this manuscript is founded on an extensive review of the literature that centers on the control of trains and the implementation of regenerative braking systems. As for the writing structure of this paper in part 1 we provide a brief introduction to the background behind the necessity of energy efficiency in urban electrified railway operations. Part 2 introduces the basic principles and problems of Train Control and regenerative braking systems. Part 3 discusses works that have been done for years in the field of Train Control and the utilization of regenerative braking system. Finally, in Part 4 we present the main conclusions and directions for future research.

2 THE BASIC PRINCIPLE AND PROBLEM OF EFFICIENCY ENERGY

2.1 Train Control

The cost of fuel expenditure in railway operations is a routine and mandatory cost incurred by every railway operator in the world. It is estimated that the cost of purchasing and maintaining locomotives throughout their lifetime is equivalent to the total fuel consumption cost of the locomotive [3]. The implementation of energy-efficient driving tactics to curtail fuel consumption is an utmost concern. As such, the establishment of a proficient train control system would be exceedingly advantageous for all railway operators worldwide.

The regulation of trains' speed and acceleration, to reduce fuel or energy usage, is known as train control. Train control can be achieved through optimal adjustment of the speed and acceleration applied to each phase of the train journey, taking into account factors such as the topography of the track, load, and distance that must be traveled in a certain time.

Let's consider the example of a train that moves between stations on a track with varying gradients. To achieve the intended goal within the designated time, it would be favorable to minimize the use of fuel as much as possible. To accomplish this, a predetermined fuel supply rate is established for each traction control level. This rate directly affects the locomotive's output power, and the resulting acceleration is always non-negative. A single brake control provides consistent negative acceleration. Dynamic braking is now only used to control the train's speed. In Train Control, the train is controlled by a condensed set of traction controls and a decisive braking phase. At each level, the control settings remain the same. The traction phase is classified as a power phase or a coasting phase if the fuel supply rate is zero. Each control strategy is generated by the motion equation with a unique speed profile. Therefore, a technique is considered usable if it meets the time and distance limitations. [3].
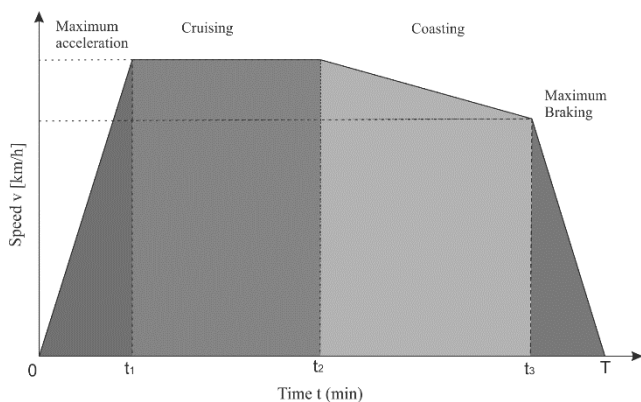

Figure 1. Optimal control in flat gradient [10]

As shown in Figure 1. there are four phases on the speed vs. time curve:

1) Acceleration: In this phase, the train will be given acceleration by increasing the power supplied to the engine. The train will continue to be given acceleration until it reaches the desired or designated maximum speed. This acceleration phase typically requires more energy.
2) Cruising: After reaching the maximum speed, the train will enter the cruising phase. In this phase, the train will maintain the speed that has been achieved without requiring much energy. This phase is usually the most energy-efficient.

3) Coasting: In this phase, the power supplied to the engine is reduced so that the train will start to slow down on its own. This phase can help reduce energy consumption, especially if the train is traveling on a downward slope.
4) Braking: In this phase, the train will be given brakes to reduce speed or stop the train. This phase typically requires relatively more energy but is important to ensure passenger safety and comfort as well as stopping the train at the destination station.

If the motion equation is used to determine a unique speed profile for each control strategy, it is possible to consider an energy-efficient strategy as viable as long as it meets the distance and time limitations.

2.2 Utilization of Regenerative Braking

Regenerative braking is an energy recovery method employed in electric trains that capitalizes on the kinetic energy produced by the train's motion as it decelerates or halts, which is subsequently transformed into electrical energy that can be repurposed to fuel the train [11].
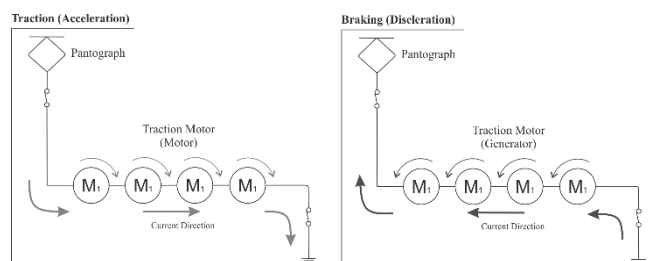

Figure 2. Regenerative braking principle [12]

The principle of its operation is that when the braking system is activated, the electric motor in the vehicle functions as a generator, allowing the kinetic energy generated by the vehicle's motion to be converted into electrical energy [13].

Electric energy can be supplied to the pantograph (overhead power source) or stored in energy storage systems such as batteries, flywheels, or supercapacitors. This stored energy can be used later to accelerate the train. By employing this method, electric trains can effectively reduce energy consumption and improve energy efficiency.

To optimize the employment of regenerative braking energy, the scholarly community has researched three primary approaches:

- Optimizing train schedules to synchronize acceleration and deceleration to fully absorb regenerative braking energy.

- Installing an energy storage system (on-board and stationer/wayside) to store the energy generated by the regenerative braking process.
- Installing a reversible substation to return electrical energy to the main grid

3 METHODS AND SOLUTION OF TRAIN CONTROL AND UTILIZATION OF REGENERATIVE BRAKING

3.1 Train Control

In this particular section, an extensive examination of the literature regarding the Train Control (TC) model shall be conducted, as well as the techniques employed to solve it. The TC model can be distinguished into two distinct parts: those with regenerative braking and those without. There are numerous classifications that can be obtained through the use of solution methods. The two primary solution approaches that can be identified are explicit or implicit reliance on the optimal control structure, which originates from the optimality conditions of Pontryagin's Maximum Principle (PMP).

3.1.1 Without regenerative braking

Kunihiko Ichikawa conducted the inaugural study on energy-efficient train control in Japan. The fundamental energy-efficient train control model was employed by simplifying the resistance force. As the differential equations were non-linear, Pontryagin's Maximum Principle was utilized by Ichikawa to obtain analytical expressions for various regimes. He scrutinized all four driving regimes on level tracks, namely maximum acceleration (MA), cruising by partial traction force (CR), coasting (CO), and maximum braking (MB), as well as the results of the optimal control regulations. Despite the study's extensive idealization of the train's equations of motion, the author concluded that the fundamental principle of a train's optimal functioning had been made clear. He believed that this study would serve as the beginning of reputable and scientific research on how to reduce the amount of energy used by railway operations daily [14].

H. Strobel described a technique for designing optimal train control algorithms that reduce the consumption of traction energy for electric and diesel locomotives. The approach employs Pontrjagin's Maximum Principle and Bellman's Method of Dynamic Programming to solve the optimal control problems of a train traveling between two stations and passing a sequence of stations. The resulting control algorithms were implemented using on-board microcomputers, and extensive experimental studies were conducted with urban and suburban passenger trains to demonstrate the ability of the developed on-board control system to save fuel and energy. The researchers identified five driving modes: Maximum acceleration (MA), Cruising with partial traction force (CR1), Coasting (CO), Cruising with partial braking (CR2), and Maximum braking (MB). The onboard control system, which was developed using the control algorithms derived from this study, showed fuel and energy savings of 5-15% and 10-20%, respectively, in the comprehensive experimental studies carried out with urban and suburban passenger trains [15].

The University of South Australia (UniSA) has been conducting research on optimal train control since 1982, which originated from a study by M.I. Ian Peter Milroy [16], Focusing on continuous train control, this model bears resemblance to P. Howlett's foundational model, which incorporates Pontrjagin's Maximum Principle [3]. Based on Milroy's investigation into urban railway transportation, three optimal driving strategies were identified for urban trains on level tracks with a fixed speed limit: Maximum Acceleration (MA), Coasting (CO), and Maximum Braking (MB). P. Howlett utilized Pontrjagin's Maximum Principle to prove mathematically that the most effective driving approach for a level track with a set speed limit involves four driving techniques, among which cruising was already discovered by H. Strobel and P. Horn [15]. UniSA translated the theoretical concept of energy-efficient and continuous train control into practice through a profit-oriented system named Metromiser. This system has two components: providing energy-efficient trip schedules for urban and suburban passenger train services and guiding engineers on how to minimize energy consumption to achieve these schedules. The Driver Advisory Systems component of Metromiser guided engineers on when to coast and when to brake using visual and auditory signals to reduce energy consumption. During the coasting and braking phases, the Metromiser assumed a constant effective gradient. This system was first tried out successfully on suburban trains in Adelaide, Australia in 1984. Trains equipped with Metromiser achieved energy savings of over 15% and improved punctuality compared to those without it. Given the short distances between stations on suburban trains, P. G. Howlett, I. P. Milroy, and P. J. Pudney identified the coasting phase as the most crucial driving strategy [2].

I. M. Golovitcher proposed a method to calculate the most efficient controls for rail or fixed-path vehicles, aiming to minimize energy consumption by considering external forces and the varying maximum speed according to the vehicle's position. This method

employs the principle of maximization to identify optimal controls, switch graphs, and optimality conditions, and a computation algorithm is established based on these outcomes. Overall, I. M. Golovitcher provided an exemplification of optimal controls and explored several potential applications of the proposed method, including train schedule optimization. This indicates that modifying the arrival time of a train at a specific station without disrupting the operations of other trains could allow for a redistribution of total travel time to reduce energy consumption. As an illustration, this method was applied to optimize the schedule for a 120-kilometer railway stretch involving local, inter-city, and freight traffic, resulting in energy savings of 7% [17].

In their study, T. Albrecht investigated the optimal control strategy for an individual train through the utilization of linear resistance equations. To calculate displacement curves, the authors used Simulink. They then identified the best switching points for the reverse trajectory from the destination station. This control algorithm was integrated into a Driver Advisory System in a train driver simulator at Dresden University of Technology. The system was tested in real-time passenger operations on the S1 suburban railway line in Dresden, as explained by Albrecht (2005). These real-time tests were successful and resulted in energy savings of 15% to 20% compared to manual driving methods [18].

Five distinct driving regimes based on Pontryagin's Maximum Principle (PMP) have been identified by R. Liu. These regimes include partial power and partial braking cruising strategies. The author's conclusion is that the optimal cruising speed is the maximum speed.. To determine the most effective control approach, the researchers have designed four control discontinuity graphs that illustrate the transitions among the five driving regimes. The graphs take into account the speed and speed limits at the discontinuities. The distance was partitioned into intervals with consistent resistance levels, and a constant Hamiltonian was applied within each interval to establish complementary optimality conditions. To determine the cruising speed and construct the optimal trajectory, a numerical algorithm incorporating both outer and inner loops was formulated. This algorithm was utilized in simulations and optimization for crew training and schedule improvement. The results of the simulations yielded a 3% reduction in energy consumption during the Automatic Train Operation (ATO) metro system simulation [19].

The study performed by S. Aradi presented a prognostic optimization model intended to calculate the speed profile of a train. The fundamental objective of this model is to minimize energy usage while taking into account variations in gradients and speed constraints. The algorithm anticipates the train's speed profile by examining its present location and the distance it will travel. Using a multi-objective function, the model aims to enhance punctuality and reduce overall energy consumption. The researchers successfully addressed this model by applying sequential quadratic programming techniques. They employed this model in a particular case study involving a train pulled by a locomotive that traveled along a 15-kilometer stretch of the Swiss railway line linking Fribourg and Bern. The outcomes of the investigation illustrated a noteworthy energy conservation of 15.3% when compared to traditional operational practices [20].

According to the scholarly work of T. Albrecht and A. Binder, strict adherence to a pre-determined arrival time may not always be the most effective means of conserving energy, as it may require trains to adjust their speed and consume additional energy. The authors recommended using time windows to promote energy-efficient driving practices by specifying the earliest and latest permissible arrival times at a given location.. A case study conducted in the United Kingdom demonstrated that utilization of a time window spanning either 1 or 3 minutes could lead to additional energy savings of 13% and 18%, respectively, compared to instances in which no time window was employed [21].

By creating a train resistance equation, A. Trivella created a new model that takes into consideration how the direction and speed of the wind affect train velocity. A network that takes into account the updated motion relations of trains and the nonlinear discretization of speed variables was created by the researchers. To determine the most energy-efficient route, a line-search framework and dynamic programming shortest path method were utilized. The proposed train trajectories were more effective and had a different shape when compared to typical speed profiles calculated without wind information. Taking into consideration the influence of wind speed and direction on the train's velocity, it was found that the suggested equation for train resistance exhibited greater precision than the currently existing models. The recommended approach may be used to determine energy-efficient railway routes that make use of wind information that is available before train departure. It is also computationally efficient. The suggested network for distance speed assimilates authentic train motion relations that are updated with wind data. This network relies on a nonlinear discretization of speed values,

which renders it more balanced than previous networks [22].

3.1.2 Methods with regenerative braking

Regenerative braking is discussed in this section under the heading "energy efficiency." The amount of energy that can be saved in the operation of urban electric trains grows with the adoption of regenerative braking systems as energy recovery. However, to utilize the regenerative braking system, adequate and ideal timing is needed to absorb the energy produced.

Research on Train Control (TC) was done by I. A. Asnis who took into account the regenerative braking system parameter as an energy recovery. The optimum control issue with phase limits is solved using the maximum principle, and several trajectory types and assumptions are possible. The study's findings demonstrate that the optimum control with phase constraints problem may be resolved using the maximum principle [23].

In their research on train control (TC) and regenerative braking systems, R. Franke introduced a novel algorithm aimed at reducing the amount of traction energy utilized by a train. The algorithm used an alternative formulation to solve nonlinear equations of motion for track segments with constant parameters.. To efficiently tackle the optimal control problem, the algorithm employs a discrete dynamic programming (DDP) approach, which is deemed suitable for implementing a Nonlinear Model Predictive Controller (NMPC) in real time. The algorithm considers the efficiency of the propulsion system based on the set point to minimize electrical energy consumption from the power supply. The simulation and practical measurements validate that the algorithm can achieve energy savings ranging from 10% to 30%, contingent on the operating conditions [24].

J. Qu had developed an optimization model and numerical algorithm for creating an energy-efficient driving plan for trains. The optimization model is used to identify the best operational modes, while the numerical algorithm is used to generate a speed curve that saves energy. Moreover, the authors have utilized the maximum principle to demonstrate that the speed-holding operation mode is the most energy-efficient when braking energy is entirely recovered. The proposed energy-efficient driving strategy for trains has been efficacious in reducing energy consumption. The identified optimal operation modes for railway systems with high regenerative energy efficiency are full traction, speed-holding, and full braking. It is recommended to avoid the coasting regime. This algorithm can be used for online computation and re-

computation to update operation commands from the Automatic Train Supervision (ATS) system when the Automatic Train Operation (ATO) system receives them [25].

X. Luan have employed an integrated optimization approach that takes into consideration both train- and traffic-related properties, such as speed trajectories, to concentrate on delay recovery. We have developed a method that tackles two critical issues in train operations: delays and energy usage. Our approach involves using energy-based equations to improve efficiency and minimize delays simultaneously. This strategy forms the bedrock of our optimization techniques. According to our research, regulating train speed can cut down energy usage and delays by 4.0% and 5.6%, respectively. We have also found that utilizing regenerative braking can lead to a considerable 22.9% reduction in energy consumption [26].

3.2 Utilization of Regenerative Braking

The utilization of a regenerative braking system (RBS) as an energy efficiency method in urban electric trains has a significant percentage of energy savings compared to the train control method discussed earlier. This is because, in this method, there is a parameter of energy generated to reduce total energy consumption. In the use of RBS, there are three most popular methods, including timetabling, Energy Storage System, and reversible substation, which will be discussed in the next chapter.

3.2.1 Timetabling

Timetable is the most commonly used method for utilizing regenerative braking systems (RBS). This is because the cost of building and implementing this timetable method is relatively small compared to other methods of utilizing RBS, such as the application of energy storage systems, both wayside and on-board. We do not need to buy additional equipment or components to manage the use of energy in operating urban electric trains.

Unlike the train control method discussed earlier, which focuses on energy savings by minimizing energy use in moving trains from one station to another, the timetable method in regenerative braking systems discusses how an urban electric train can optimize the renewal of energy generated by the traction motor that changes function as a power generator. Then, this energy is used for other train tractions, so that the total energy consumption can be minimized because the supply of energy from regenerative braking systems is optimized as renewable energy.

Many urban electric train companies in the world are still considering the application of this method. This is because the main focus of railway companies today is the excellent service offered to customers, one of the parameters being the short total travel time for passengers. Energy saving through RBS becomes a secondary parameter when the main focus is on optimizing passenger wait times. This is because when we increase the headway or train frequency to minimize passenger wait times, it will have a significant impact on the increased use of electric energy. Therefore, to achieve both main objectives, more in-depth research is needed based on the desired and prioritized limitations. In any case, energy efficiency discussed in section 1 is an important parameter that must be considered to face future problems.

A timetable was created by M. Peña-Alcaraz to maximize the use of regenerative-braking energy in underground rail systems through coordinating train movements. This was achieved using a mathematical programming optimization model that synchronized incoming train braking with the acceleration of outgoing trains. Furthermore, a power flow model of the electrical network was designed to determine the power-saving factor of each synchronization event, which resulted in improved synchronization with minimal energy losses. The proposed optimization and power flow models proved to be effective in scheduling the Madrid underground system, resulting in a notable 7% reduction in energy consumption [27].

In T. Albrecht's study, a high-speed and precise network simulator was used to model the power supply system's impact, including regenerative braking effects. To achieve the utmost efficiency in regenerative energy usage, several approaches were implemented, which effectively utilized synchronized train controls. Most of these controls regulated train dwell time to increase the use of regenerative energy by scheduling movements that coordinated acceleration and braking trains. Nonetheless, this approach encountered two challenges: the diminished punctuality of train departures due to the priority assigned to accommodating passenger boarding and alighting times to enhance customer satisfaction, and the utilization of travel time reserves as additional dwell time, which could also serve as a reserve for extended control phases during the initial stages of train travel along the route. This outcome remained unaffected by the mode of train operation, whether manual or automatic. In response to these hindrances, T. Albrecht introduced an alternative strategy that involved controlling train running times instead of train dwell times to synchronize acceleration and braking

stages. Genetic Algorithms (GA) were applied to minimize energy consumption in systems with constant headway operations. A case study was carried out on a specific line within the Berlin S-Bahn network. The study concluded that achieving an optimal combination of train headway and synchronization time would enable the implementation of a controller based on Dynamic Programming to minimize individual train energy consumption. Nevertheless, when these criteria were not met, modifying train running times could significantly diminish power peaks and energy consumption, ultimately leading to reduced energy expenses in rail transit systems [28].

X. Li presented a cooperative scheduling technique aimed at enhancing energy efficiency and reducing the operating costs of subway systems. The method optimizes regenerative energy by synchronizing acceleration and braking times of successive trains. her research determined the overlapping time of successive trains concerning peak and off-peak situations, formulated an optimization model, and proposed a heuristic algorithm to solve it. Numerical experiments were conducted to evaluate the method's performance, which demonstrated significant improvements in energy efficiency, punctuality, and reliability of subway systems. The experiments revealed that the cooperative scheduling approach can decrease subway system energy consumption by up to 30% and total travel time by up to 20%. Moreover, the method proves to be resilient to variations in passenger demand and train speed [29].

To enhance energy efficiency within metro train systems, S. Das Gupta and X. Li introduces a novel technique to develop energy-efficient schedules for metro rail networks. This approach involves two optimization phases. The first phase minimizes overall train energy consumption, while the second phase maximizes the utilization of regenerative energy generated during train braking. This proposed method can significantly assist traffic management in devising more effective plans for energy-saving operations. The technology discussed in this study can be applied to high-speed trains and various passenger train types beyond metro rail systems. To demonstrate the efficacy of their strategy, the authors employ a genetic algorithm and conduct a simulation study using the actual Beijing Metro Yizhuang Line. The research findings reveal that employing the minimum permissible headway of 90 seconds leads to a maximum energy savings rate of approximately 25%, as indicated by numerical analyses, with longer headways yielding lower energy savings rates. Moreover, in comparison to the two-step optimization approach undertaken by X. Li, their method is capable

of reducing net energy consumption by around 20% [30], [31].

S. Yang introduce a dual-objective optimization framework aimed at concurrently refining the schedules for multiple trains over an extended period in a metro network. This approach encompasses the optimization of arrival, departure, and dwell times, while also considering energy distribution and passenger assignment, all to achieve optimal passenger travel duration and energy efficiency. They put forward an algorithm based on NSGA-II to effectively identify the Pareto frontiers. The variables employed in the optimization model to enhance passenger wait times and energy usage encompass train arrival, departure, and dwell intervals, passenger allocation to individual trains, regenerative energy assignment to each train, train velocity, station spacing, train capacity, passenger count at each station, and energy consumption for each train. The outcomes of numerical experiments demonstrate the bi-objective optimization model's potential to heighten energy efficiency and passenger travel times within the metro system. The researchers identified that the application of regenerative energy can yield enhancements of up to 20.09%, and the overall travel duration can be reduced by as much as 3717 hours when compared to a fixed regular timetable, utilizing a selected optimized solution from the Pareto frontier [32].

3.2.2 Energy Storage System

Energy Storage System (ESS) technology plays a crucial role in reducing energy consumption in electric trains [33]. ESS technology involves the use of advanced batteries or other storage devices to store and release electrical energy as needed. By implementing ESS in electric trains, several benefits can be achieved in terms of energy efficiency. Urban electric trains often utilize regenerative braking systems, which convert the kinetic energy of the moving train into electrical energy during braking. The ESS can capture and store electrical energy for reuse, reducing train energy consumption.

ESS in electric trains can be divided into two main types that are on-board (inside the train) [34]–[36] and stationary (along the track) [9], [37]–[40]. On-board ESS refers to using energy storage systems in the electric train, while Wayside ESS refers to using energy storage systems along the train tracks, often seen at stations or substations.

R. Barrero examines the usage of emission-reducing electric light rail vehicles in urban settings. By incorporating an Energy Storage System (ESS) to facilitate energy recuperation, it is feasible to enhance the energy efficiency of these vehicles. The installation of stationary ESS powered by supercapacitors along the metro line is suggested in this study to maximize energy efficiency and cut expenses. A Matlab/Simulink model utilizing an effect-cause or backward-looking approach has been developed to explore the impact of energy storage system (ESS) size and distribution along the metro route on the light rail vehicle and power grid. The ESS configuration has notable effects on energy content, voltage fluctuation, maximum current, and power losses. To regulate energy flow about grid voltage operation and ESS charge condition, a power flow controller is recommended. The results demonstrate the advantageous application of stationary ESS on a metro line in terms of energy savings, with potential savings ranging from 11% during peak times to 26% on nights and weekends [39].

C. Sumpavakup has proposed a strategy to optimize energy savings in a DC electric railway system. The strategy involves implementing an on-board Energy Storage System (OBESS) for peak demand shaving. This system stores the braking energy and sends it back to the power grid at an appropriate time to reduce peak power at each substation.. The Bangkok Mass Transit System (BTS) - Silom Line was used to test and verify the proposed strategy. The study compares the effectiveness of the proposed strategy using two different travel time controls, coasting, and deceleration. Using a simulation model, the authors analyzed the energy consumption and peak power reduction resulting from the proposed strategy. Their study showed that the use of an on-board Energy Storage System (OBESS) for peak demand shaving was effective in reducing peak power at substations and achieving net energy savings in the DC electric railway system. The findings of the study reveal a significant reduction in peak substation power by 63.49% and a consequent reduction in net energy consumption by 15.56% through the implementation of coasting and deceleration travel time controls [34].

S. Ahmadi proposed a method to optimize speed profiles and energy storage systems (ESS) simultaneously. The case study analyzed Mashhad LRT Line 1, focusing on effectively utilizing regenerative braking energy for urban electric rail transportation. The method includes two processes optimizing the stationary supercapacitor ESS and determining the ideal speed profile. The study demonstrates that optimizing speed profiles and energy storage systems can significantly reduce energy consumption in urban electric rail transportation. According to the research findings, determining the most efficient speed profiles for Energy Storage Systems (ESSs) can result in a conservation rate of only

11.6%. Nevertheless, if the optimal speed profiles are first identified, and subsequently, the accurate capacity of ESSs is calculated, the savings in energy can increase significantly up to 20%, thereby reducing the overall capacity of ESSs. By optimizing the stationary supercapacitor ESS and identifying the appropriate speed profile and energy storage, the required energy storage system capacity can be minimized, leading to a reduction in costs [41].

3.2.3 Reversible Substation

Reversible substation is an energy efficiency technique used in electric railway systems. This method involves the implementation of a substation that can operate in both consumption mode and energy generation mode, allowing for the recovery and reuse of regenerative braking energy. In conventional electric railway systems, when a train applies brakes, its kinetic energy is converted into heat and waste, resulting in energy loss. However, with the reversible substation method, the regenerative braking energy is captured and returned to the power supply network [42].

H. Ibaiondo Introduced a new converter topology and feedback energy recovery system to overcome the non-reversible nature of direct current overhead catenary-based rail systems, which limit the reuse of kinetic energy lost during braking. Real data from multiple unit electric units, including traction profiles, braking power, and speed data from all existing routes, were used to validate and optimize the proposed energy recovery system. The results show that a single recovery substation can recover between 8% and 25% of the energy lost during train braking. A prototype of the proposed system has been in operation since August 2009, and on working days it recovers between 1800 kWh and 4000 kWh of energy, depending on the voltage levels on the grid. The energy recovery increases up to 5000 kWh during weekends [43].

D. Roch-Dupré examined ways to enhance energy efficiency in DC electric train systems by utilizing Reversible Substations or Energy Storage Systems to optimize the utilization of regeneration energy generated by trains during braking. If energy storage systems' optimal capacity is determined based on typical speed profiles, the energy savings will only be 11.6% according to the results. However, by first determining the ideal speed profiles and then calculating the optimal capacity of ESSs, energy savings can be substantially increased to 20%, and the aggregate capacity of ESS can be reduced accordingly. By optimizing the fixed supercapacitor ESS and ascertaining the optimal speed profile and energy storage, the requisite capacity of the energy storage system can be reduced, thereby curtailing the expenses.

The proposed model was applied to a case study that focused on installing RSSs, and the results showed that the accuracy of the traffic model significantly affects the simulation results. The study concludes that installing RSSs or ESSS is an effective strategy to improve energy efficiency in DC electric train systems. This information is important for train operators to evaluate the infrastructure and make informed decisions to increase energy efficiency [44].

K. Almaksour performed optimization to reduce energy consumption from the 6.6 km long metro railway network in Thessaloniki (Greece) by implementing a reversible substation system and applying a wayside storage system. The problem of optimization was approached as a quadratic programming problem, with the goal of minimizing energy consumption in the railway system. Based on simulation results, the proposed optimization strategy showed a significant improvement in railway system performance, as compared to local control and unidirectional substations. Voltage variations from the "no-load" voltage value were used to gauge how well the suggested technique performed. For example, the "reversible substations" scenario reduced the train voltage variations in track 1 and track 2 by 44.32% and 37.01%, respectively, resulting in an 8% reduction in power losses (from 23.53 to 21.64 kWh) compared to the local control method. Additionally, the adoption of wayside storage devices decreased voltage variations in tracks 1 and 2 by 19.6% and 18.5%, respectively. This resulted in a 4% decrease in power losses from 23.95 to 23.03 kWh [45].

F. Cascetta promoted and puts into practice a technique to assess how regenerative braking systems (RSS) affect energy efficiency from the viewpoint of train operators and designers. Using information gathered from a measuring campaign conducted on metro trains in commercial operation with RSS, specifics concerning the statistical analysis of the energy flow exchanged between trains and overhead connections are provided. A unique measurement device that can do thorough energy analyses was created for this purpose and put on trains running on the metro line servicing the city of Madrid. According to statistics, a new index (Lu) has an average value of 10% without RSS and 8% with RSS under heavy traffic conditions. In low-traffic situations, these percentages rise to 22% and 16%, respectively, showing that inverted substations have a higher effect when there are fewer running trains. By matching data from each braking event, the behavior of a new index (Lu) vs. real supply voltage ratios was assessed, demonstrating that the influence of RSS grows as voltage ratios increase. With fewer trains, these comparison findings demonstrate that

implementing RSS has the potential to considerably increase overall efficiency [46].

4 CONCLUSION

In incorporating energy efficiency in urban electric railway systems, several methods can be used, including the primary and popular methods such as train control and the utilization of regenerative systems. These methods are commonly applied to reduce energy consumption in both conventional and urban electric railway operations.

Train control is a conventional method that has been applied since the 1960s, and numerous studies have been conducted on it until recent years. Meanwhile, the regenerative system has been known since the 1980s, making it a relatively new method compared to train control. In principle, these two methods have quite fundamental differences in their implementation, resulting in significantly different percentages and results. This is because train control aims to minimize fuel consumption during the movement from the origin to the destination station, while the regenerative braking system aims to maximize the absorption of energy generated during the braking process, meaning that there is energy generated or recovered in this process. This difference in principles between the two methods results in significant differences in their output. However, both methods can be used simultaneously to achieve higher energy efficiency.

In utilizing a regenerative braking system, it is divided into several methods including timetabling, the use of energy storage systems (on-board and wayside), and the use of reversible substations. Each method has its advantages and disadvantages.

Timetabling is advantageous because of its low implementation cost as no additional costs are required. The timetabling method has a high level of efficiency when the optimization model used has very high accuracy towards a system. However, as the constraints increase, such as the number of operating trains being relatively high, the distance between stations being relatively different, the stop time at stations being variable, and the speed of trains between stations is limited, the problem becomes more complex and it becomes more difficult to find an optimal solution.

Energy storage systems have the advantage of higher energy absorption compared to timetabling because the energy generated by the braking process can be directly absorbed by supercapacitors to be used in the acceleration phase. In addition, ESS can reduce excessive voltage in the overhead electrical system. However, in its application, it requires a very large initial cost. In addition, it requires a large enough space for application, especially for those applied on trains. This will affect the increase in energy consumption because the weight of the train will increase.

The last method is the reversible substation method. This method allows the current to flow in two directions between the power supply and the electric train so that the energy generated from braking can be returned to the main power source. Although the energy generated from braking can be directly returned to the main power source, from the research that has been done, there is still energy lost in the conversion process through the inverter and not returned in full to the main power source. In addition, the high initial cost makes this method rarely applied.

Combining energy efficiency methods is a future research area that may improve energy efficiency more than just using one or two methods. However, to the author's knowledge, there is still limited research that combines many methods in energy efficiency. This paper provides an overview to the reader about the methods commonly used in energy efficiency in urban electric trains.

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