GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA

FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2025

THIRD INTERNATIONAL CONFERENCE

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FACULTY OF ELECTRICAL ENGINEERING

ТРЕТА МЕЃУНАРОДНА КОНФЕРЕНЦИЈА
THIRD INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2025

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PREFACE

The Third International Conference "Electrical Engineering, Technology, Informatics, Mechanical Engineering and Automation – Technical Sciences in the Service of the Economy, Education and Industry" (ETIMA'25), organized by the Faculty of Electrical Engineering at the "Goce Delchev" University – Shtip, represents a significant scientific event that enables interdisciplinary exchange of knowledge and experience among researchers, professors, and experts in the field of technical sciences. The conference was held in an online format and brought together 78 authors from five different countries.

The ETIMA conference aims to establish a forum for scientific communication, encouraging multidisciplinary collaboration and promoting technological innovations with direct impact on modern life. Through the presentation of scientific papers, participants shared the results of their research and development activities, contributing to the advancement of knowledge and practice in relevant fields.
The first ETIMA conference was organized four years ago, featuring 40 scientific papers. The second conference took place in 2023 and included over 30 papers. ETIMA'25 continued this scientific tradition, presenting more than 40 papers that reflect the latest achievements in electrical engineering, technology, informatics, mechanical engineering, and automation.

At ETIMA'25, papers were presented that addressed current topics in technical sciences, with particular emphasis on their application in industry, education, and the economy. The conference facilitated fruitful discussions among participants, encouraging new ideas and initiatives for future research and projects.

ETIMA'25 reaffirmed its role as an important platform for scientific exchange and international cooperation. The organizing committee extends sincere gratitude to all participants for their contribution to the successful realization of the conference and its scientific value.

We extend our sincerest gratitude to all colleagues who, through the presentation of their papers, ideas, and active engagement in discussions, contributed to the success and scientific significance of ETIMA'25.

The Organizing Committee of the Conference

ПРЕДГОВОР

Третата меѓународна конференција „Електротехника, Технологија, Информатика, Машинство и Автоматика – технички науки во служба на економијата, образованието и индустријата" (ЕТИМА'25), организирана од Електротехничкиот факултет при Универзитетот „Гоце Делчев" – Штип, претставува значаен научен настан кој овозможува интердисциплинарна размена на знаења и искуства меѓу истражувачи, професори и експерти од техничките науки. Конференцијата се одржа во онлајн формат и обедини 78 автори од пет различни земји.

Конференцијата ЕТИМА има за цел да создаде форум за научна комуникација, поттикнувајќи мултидисциплинарна соработка и промовирајќи технолошки иновации со директно влијание врз современото живеење. Преку презентација на научни трудови, учесниците ги споделуваат резултатите од своите истражувања и развојни активности, придонесувајќи кон унапредување на знаењето и практиката во релевантните области.

Првата конференција ЕТИМА беше организирана пред четири години, при што беа презентирани 40 научни трудови. Втората конференција се одржа во 2023 година и вклучи над 30 трудови. ЕТИМА'25 продолжи со истата научна традиција, презентирајќи повеќе од 40 трудови кои ги отсликуваат најновите достигнувања во областа на електротехниката, технологијата, информатиката, машинството и автоматиката.

На ЕТИМА'25 беа презентирани трудови кои обработуваат актуелни теми од техничките науки, со посебен акцент на нивната примена во индустријата, образованието и економијата. Конференцијата овозможи плодна дискусија меѓу учесниците, поттикнувајќи нови идеи и иницијативи за идни истражувања и проекти.

ЕТИМА'25 ја потврди својата улога како значајна платформа за научна размена и интернационална соработка. Организациониот одбор упатува искрена благодарност до сите учесници за нивниот придонес кон успешната реализација на конференцијата и нејзината научна вредност. Конференцијата се одржа онлајн и обедини седумдесет и осум автори од пет различни земји.

Изразуваме голема благодарност до сите колеги кои со презентирање на своите трудови, идеи и активна вклученост во дискусиите придонесоа за успехот на ЕТИМА'25 и нејзината научна вредност.

Организационен одбор на конференцијата

СОДРЖИНА / TABLE OF CONTENTS:

Трета меѓународна конференција ЕТИМА
Third International Conference ETIMA
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BATTERY STORAGE IN TRACTION POWER SUPPLY

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Abstract

Modern traction power supply systems face growing demands for greater efficiency, reliability, and capacity. This paper explores the integration of battery energy storage systems as a key technology to address these challenges. By capturing and reusing energy from regenerative braking, battery energy storage systems significantly enhances system performance. Deployed as either stationary wayside units or on-board systems), this technology offers three primary benefits: improving power efficiency through peak shaving and reducing grid dependency; increasing network capacity to support more or longer vehicles without costly infrastructure upgrades; and mitigating line voltage fluctuations caused by vehicle acceleration and braking. This paper is the basis for further research into the application of battery energy storage systems in the tram and trolleybus network of Bratislava. The findings from this paper will be applied with regard to the specifics of the transport network and its traction system in the authors further research.

Key words

Traction power supply, Battery storage system, wayside/on-board energy storage systems

Introduction

Modern traction power supply systems for railways, trams, trolleybuses, and subways face ever-increasing demands for efficiency, reliability, and sustainability. While traditional systems relied solely on energy from external grids, current challenges such as emission reduction, improving capacity, cost savings, and the integration of renewable sources require innovative solutions. In this context, battery energy storage systems (BESS) are becoming a key technology. Their primary purpose is not only to supply energy, but also to manage it intelligently, minimizing operational losses and optimizing overall consumption. Depending on how the BESS is designed, it can have different effects on the traction system. For example, the desired improvement in the traction system can be:

- Improving power efficiency of the system by lowering power transfers required between the traction system and distribution network.
- Increasing the number of vehicles the system can supply by improving the capacity of the system.
- Mitigating voltage fluctuations of the system caused by acceleration and regenerative braking.

The base principle of BESS in traction applications is optimizing the energy balance between the traction vehicles and the supply. The most prominent power fluctuations of energy are caused by acceleration and braking of vehicles. The effective usage of BESS in traction requires the use of regenerative braking capable vehicles. Most modern trains, trams and trolleybuses are equipped with this capability. Older types of vehicles might see little to no change in their efficiency, especially when using standard non-regenerative braking.

Another usage case for BESS is not for power optimalization, instead it is intended for use on sections without proper traction infrastructure. The vehicles in this case are equipped with an on-board energy storage device (OESD), instead of the wayside energy storage devices (WESD) as was the case in previous text [1]. The BESS receives energy on parts of the traction network with infrastructure. The energy stored in the system can then be utilized on parts of the route that do not have the required infrastructure, such non-electrified parts of a railway or tram network. This can reduce the size of the traction system required for the efficient transport of people and materials.

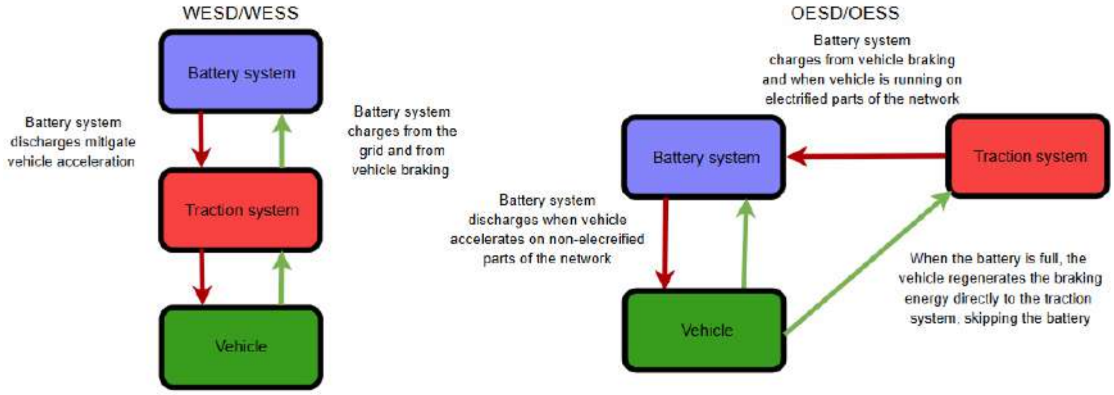

Fig. 1. A comparison of wayside and onboard energy storage devices (or energy storage systems) with the power flow to and from the vehicle designated with red and green arrows

Methods

Battery storage systems are increasingly being explored and implemented in traction applications to enhance energy efficiency, reduce operational costs, and improve grid stability. These systems primarily function by capturing and storing the regenerative energy generated during train braking, which can then be reused for acceleration or fed back into the grid [3]. The deployment of these systems can be broadly categorized into two main types: wayside energy storage systems (WESS) or wayside energy recovery systems (WERS), which are stationary units installed along the railway line, and on-board energy storage systems (OESS), which are integrated within the rolling stock itself. While both approaches aim to maximize the use of regenerative braking energy, their implementation and benefits can vary depending on the specific application and operational context.

The potential uses of battery storage in traction applications are extensive. WESS for instance, can significantly reduce the peak power demand from the grid, leading to lower energy costs and a more stable power supply [2, 4, 9]. They can also be used to provide emergency power to trains in the event of a power outage, ensuring passenger safety and service continuity [8]. Furthermore, wayside storage can support the charging of electric vehicles, contributing to a broader sustainable transport ecosystem [5]. OESS on the other hand, offers the potential for catenary-free operation in certain sections of a tram or light rail network, which can be aesthetically desirable in historic city centers and can also reduce infrastructure costs [6].

Optimization models are being developed to minimize the size and energy consumption of these on-board devices, making them more efficient, cost-effective and extending their range [7].

Several real-world applications and case studies demonstrate the successful implementation of these systems. Toshiba's Traction Energy Storage System (TESS), for example, utilizes SCiB™ battery technology to efficiently store and reuse regenerative energy, and has been shown to provide significant energy savings and serve as a reliable emergency power source [8]. Similarly, ABB's Enviline energy storage system has been deployed in the Warsaw metro, where it helps to reduce energy consumption by up to 30% and stabilizes the power grid by mitigating voltage fluctuations caused by train operations [9]. These examples showcase the tangible benefits of wayside energy storage in heavy rail and metro systems. For light rail applications, research has focused on the feasibility and cost-effectiveness of both on-board and wayside systems. For example, a study on a 750V tram grid investigated a novel concept for a direct grid-coupled, uncontrolled wayside energy recovery system, highlighting the ongoing innovation in this field [2].

A key aspect of implementing battery storage systems is the selection of appropriate technology and the development of effective energy management strategies. The choice between different battery chemistries, such as lithium-ion-titanate-oxide (LTO) [2], and the use of second-life batteries [5] are important considerations that can impact the performance, lifespan, and cost of the system. Moreover, sophisticated control algorithms and energy management systems are crucial for optimizing the charging and discharging of the batteries, ensuring the most efficient use of stored energy [5, 6]. For instance, Toshiba's TESS employs an advanced V-SOC (Voltage-State of Charge) control method to reduce unnecessary charge and discharge cycles, thereby extending the battery's lifetime [8].

Battery storage systems represent a promising technology for improving the sustainability and efficiency of electric railway systems. Whether deployed as wayside or on-board units, they offer a range of benefits, including energy savings, peak power reduction, grid stabilization, and the potential for catenary-free operation. Depending on the specifics of the applied system, the initial investment costs might vary. However, the long-term energy savings and operational benefits often result in a favorable return on investment [4]. As technology continues to evolve and mature, with ongoing research focused on optimizing system design, control strategies, and battery technology, the adoption of battery storage in traction applications is expected to grow, contributing to a more sustainable and resilient future for rail transport.

Results

As explained in the introduction, the benefits of BESS in traction systems can differ with the end goal of the installation.

One of the primary benefits of integrating a BESS is improving the power efficiency of the system by lowering the power transfers required between the traction system and the distribution network. During vehicle acceleration, power demand peaks, forcing the system to draw significant energy from the grid. A BESS can discharge during these peaks, a process known as "peak shaving," to supply the required power locally. Conversely, during regenerative braking, vehicles generate electricity that would otherwise be dissipated as heat or inefficiently sent back to the grid. The BESS can capture and store this recovered energy with high efficiency. By storing braking energy and releasing it for subsequent acceleration, the BESS creates a local energy cycle, dramatically reducing the overall energy imported from and exported to the external grid, which in turn minimizes transmission losses and can lower electricity costs associated with high peak demand charges.

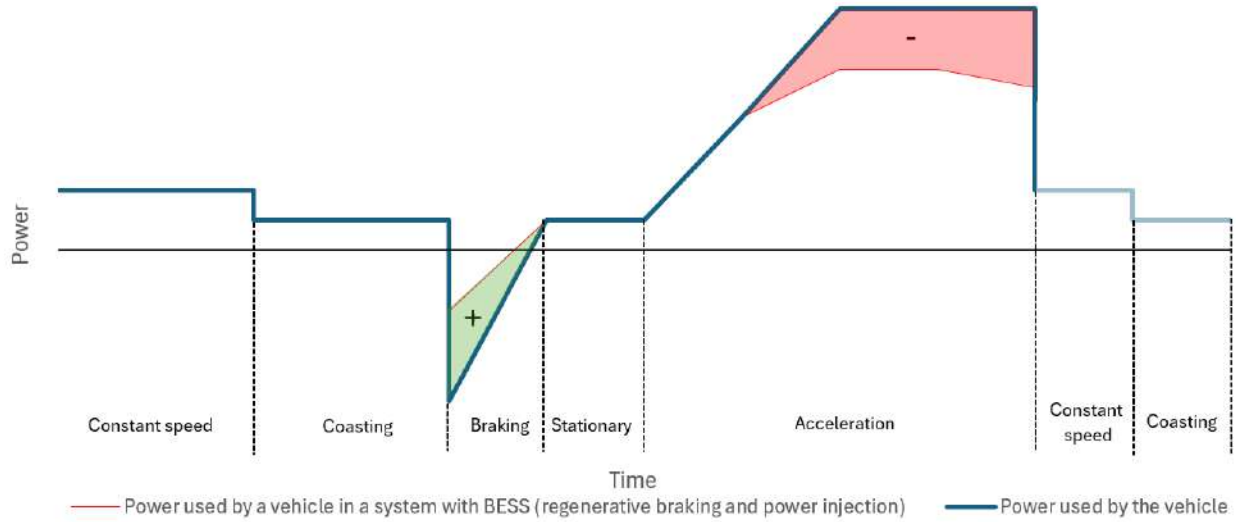

Fig. 2. Example of the power fluctuation during the standard operation mode of a vehicle, with the areas that could be reduced with the application of a battery storage system

Furthermore, a BESS can be instrumental in increasing the transport capacity of the entire system. The power rating of a traction substation often limits the number of vehicles that can operate simultaneously on a specific line, especially during peak hours when multiple vehicles may accelerate at the same time. By installing a BESS, the effective capacity of the traction power system is enhanced without requiring costly and time-consuming upgrades to the substation or the grid connection itself. The battery acts as a local power booster, supplying the additional energy needed to handle high-demand scenarios. This allows operators to increase service frequency, run longer trains, or extend the network, thereby accommodating more passengers and improving the overall throughput of the transport system.

Finally, a BESS plays a crucial role in mitigating voltage fluctuations of the system caused by acceleration and regenerative braking. The heavy current drawn during acceleration can cause a significant voltage drop along the traction line, which can impair vehicle performance and reliability. In contrast, regenerative braking injects energy into the line, causing a voltage surge that can trigger overvoltage protection systems. A BESS acts as a dynamic voltage regulator by rapidly absorbing or injecting power. It charges to absorb the excess energy during braking, preventing overvoltage, and discharges to supplement power during acceleration, propping up the line voltage. This stabilization ensures a more robust and reliable power quality, which not only protects the equipment but also maximizes the effectiveness of regenerative braking by guaranteeing the line is always able to accept the recovered energy.

This paper as well as subsequent research is based on specific feedback from the Bratislava Transport Company. Currently the BESS technology in traction applications is being examined by the author for use in the tram and trolleybus network in Bratislava, as a potentially more cost-effective upgrade to the capacity and capability of the existing network. One prevalent problem in the current traction network is periodically occurring low voltage situations. This could potentially be solved by introducing battery storage into the network. Another reason the BESS is being considered is to increase the transport capacity by introducing longer trams. These new vehicles could potentially bring imbalance to the network due to their higher current draw when accelerating. In this case the BESS would act as a sort of power balancing device, helping to mitigate the power draw and regenerative braking capabilities of different vehicles. The solution could provide the needed power capacity for longer vehicles without a lengthy and costly reconstruction of the existing traction grid infrastructure, especially when considering a low-cost, low maintenance solution, such as the direct coupled LTO battery based WESS [2]. From the tram network of Mülheim/Oberhausen, discussed by Meishiner et. al. [2], parallels can be drawn to the Bratislava tram network. Both systems work at least partially on a meter gauge (one line in Mülheim/Oberhausen network runs on 1435mm gauge track), both systems have a similar voltage (750V in Mülheim/Oberhausen to Bratislava's 600V), both have a similar length (36 km in Mülheim/Oberhausen to Bratislava's 42 km). The biggest difference in the networks is the operated vehicle types, and the frequency of the services, as the network in Bratislava serves a much more densely populated area, and therefore has a higher tram frequency. Despite this, it is a good comparison of how to design a battery storage system for a network similar to Bratislava.

Discussion

The findings presented in this paper strongly corroborate the established benefits of integrating Battery Energy Storage Systems (BESS) into modern traction power networks. The analysis reaffirms that BESS technology is a multifaceted solution capable of addressing critical challenges in efficiency, capacity, and power quality. The results align closely with the literature, such as the real-world applications by Toshiba and ABB, which demonstrate significant energy savings and grid stabilization through the effective capture and reuse of regenerative braking energy [8, 9]. The core mechanisms of peak shaving and valley filling, identified in the results, are the practical applications of the principles outlined in the methods section, effectively creating a localized energy cycle that reduces reliance on the external distribution grid.

The specific context of the Bratislava tram and trolleybus network serves as a compelling case study for the strategic deployment of BESS. The dual challenges of periodic low-voltage events and the planned introduction of higher-capacity vehicles are not unique to Bratislava; they are common issues for legacy transit systems worldwide facing modernization pressures. The traditional solution—extensive and costly reconstruction of substations and cabling—is often logistically complex, disruptive to service, and financially prohibitive. This paper positions BESS, particularly a wayside configuration (WESS), as a more agile and economically prudent alternative. By acting as a dynamic voltage regulator and a local power buffer, a WESS can directly mitigate the voltage sag issues while simultaneously providing the necessary peak power for new, longer trams. This avoids the need for a complete overhaul of the existing infrastructure, offering a targeted upgrade that resolves present issues and future-proofs the network against increased demand.

Furthermore, the consideration of a low-maintenance solution like a direct-coupled LTO battery-based WESS [2] highlights a key consideration for practical implementation: total cost of ownership. While initial investment costs are a factor, the long-term operational benefits, including reduced energy costs from peak demand charges, lower maintenance requirements compared to mechanical systems, and extended infrastructure lifespan, contribute to a favorable return on investment [4].

However, it is important to acknowledge that this analysis is primarily a feasibility assessment. A full-scale implementation would require detailed simulations based on Bratislava's specific network topology, traffic schedules, and vehicle specifications to accurately size the BESS and quantify the precise energy savings and voltage improvements. Further research should also focus on a comprehensive life-cycle cost analysis, considering battery degradation over time, and the development of an optimized energy management strategy to maximize the system's efficiency and lifespan, potentially incorporating advanced control methods like the V-SOC mentioned in the literature [8].

Conclusion

In summary, Battery Energy Storage Systems represent a transformative technology for the modernization of electric traction power supply systems. By effectively capturing regenerative braking energy and managing power flow, BESS addresses the critical needs for improved energy efficiency, enhanced system capacity, and stabilized line voltage. The deployment of this technology enables a significant reduction in operational costs by minimizing peak power demand from the grid and maximizing the use of otherwise wasted braking energy.

For transit authorities like the Bratislava Transport Company, BESS offers a strategic and cost-effective pathway to upgrade aging infrastructure without resorting to expensive and disruptive reconstruction projects. It provides a targeted solution to mitigate existing power quality issues, such as voltage drops, while simultaneously facilitating network expansion and the deployment of higher-capacity vehicles. Whether deployed as wayside or on-board units, BESS is a key enabling technology that supports the transition to a more sustainable, resilient, and efficient urban transportation future. The continued evolution of battery technology and control systems will only further solidify its role as an indispensable component of modern electrified transit networks.

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