**УДК 629.429.3:621.313** **doi: 10.20998/2313-8890.2025.11.04**

**Shtompel Oleksandr**, Post-graduate student, +38(067)993-75-69, shtompel100@gmail.com, ORCID ID: 0009-0008-1757-2650.
*O.M. Beketov National University of Urban Economy in Kharkiv*
*17, Chornoglazivska St., Kharkiv, 61002, Ukraine*
**Voronko Vitaliy**, Doctor of Science, Professor, Professor of the Department of Transport Systems and Logistics, +38(050)578-97-33, Vitaliy.voronko@gmail.com, ORCID ID: 0000-0003-1140-3983)
*O.M. Beketov National University of Urban Economy in Kharkiv*
*17 Chornoglazivska St., Kharkiv, 61002, Ukraine*

# ANALYSIS OF PROSPECTIVE TECHNOLOGIES FOR INCREASING ENERGY EFFICIENCY OF ELECTRIC TRACTION SYSTEMS OF METROPOLITAN TRAIN WAGONS

***Abstract.*** *The work includes a comprehensive analysis of promising technologies for increasing the efficiency of the electric traction system of metros. It is noted that the introduction of energy-efficient systems on metro rolling stock can significantly reduce electricity consumption for traction – up to 40 % using recuperation systems and another 10-20 % using energy storage systems. Microprocessor control systems can also help reduce electricity consumption by 10 %. The use of such systems is a promising direction for energy saving on metro rolling stock due to lower capital investments. Such systems can be installed on various types of rolling stock and will help improve traffic safety, stabilize the traffic schedule and make it easier for train drivers to control the train.*
***Keywords:*** *subway car; traction drive; optimal trajectory of subway train movement; traction motor efficiency, conditional minimization*

**Штомпель Олександр Миколайович**, аспірант, +38(067)993-75-69, shtompel100@gmail.com, ORCID ID: 0009-0008-1757-2650
*Харківський національний технічний університет міського господарства імені О. М. Бекетова*
*вул. Черноглазівська , 17, м. Харків, 61002, Україна*
**Воронько Віталій Володимирович**, д.т.н., проф., професор кафедри транспортних систем і логістики, +38(050)578-97-33, Vitaliy.voronko@gmail.com, ORCID ID: 0000-0003-1140-3983
*Харківський національний технічний університет міського господарства імені О. М. Бекетова*
*вул. Черноглазівська , 17, м. Харків, 61002, Україна*

# АНАЛІЗ ПЕРСПЕКТИВНИХ ТЕХНОЛОГІЙ ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ СИСТЕМ ЕЛЕКТРИЧНОЇ ТЯГИ ВАГОНІВ МЕТРОПОЛІТЕНУ

***Анотація.*** *У роботі проведення комплексного аналізу перспективних технологій підвищення ефективності системи електричної тяги метрополітенів. Зазначено, що впровадження енергоефективний систем на рухомому складі метрополітену може значно зменшити споживання електроенергії на тягу – до 40 % з використанням систем рекуперації та ще 10-20 % з використанням систем накопичення енергії. Мікропроцесорні системи управління також можуть допомогти скоротити споживання електроенергії на 10 %. Застосування таких систем є перспективним напрямом енергозбереження на рухомому складі метрополітену за рахунок менших капіталовкладень. Такі системи можуть бути встановлені на різних типах рухомого складу та допоможуть покращити безпеку руху, стабілізувати графік руху та полегшити керування поїздом машиністам.*

***Ключові слова:*** *вагон метро; рекуперація; оптимальна траєкторія руху поїзда метро; двигуни з PMSM, пристрої накопичення енергії.*

**Introduction.** Improving the energy efficiency of the metro is centered around three interconnected technological pillars: energy recovery, energy storage systems (ESS), and high-efficiency permanent magnet synchronous motors (PMSM). The combination of these technologies creates a qualitatively new level of energy savings, ensuring the profitability and environmental sustainability of megacities.

**Analysis of previous research.** The electrical energy consumed by urban electric transport rolling stock and obtained from the power supply system is mainly used for traction, but also to overcome the resistance of movement, including losses in the traction drive and braking processes. In most metro systems, the kinetic energy of the train can be partially recovered using regenerative braking and reused for traction, stored in on-board energy storage systems, or returned to the traction network, where it can be used by other trains or traction substations that recover it to a single power grid. Therefore, research aimed at reducing traction energy consumption usually focuses on two main aspects: minimizing the need for traction energy and maximizing the reuse of regenerative energy. To address the first aspect, one of the effective approaches involves optimizing train control strategies using the principles of optimal control theory, which determine the most energy-efficient movement profile along a certain section of track [1].

Most modern metro cars use regenerative braking systems that convert kinetic energy into electrical energy, allowing up to 30 % of the traction energy to be recovered, which can then be reused [2].

The regenerative energy can initially be used to power on-board systems, including lighting, air conditioning and safety equipment. The remaining energy is usually fed back into the traction network to assist in accelerating other trains. However, the effectiveness of regenerative braking is limited by the presence of simultaneous energy consumers in the system. To overcome this problem, modern systems use energy storage or regenerative substations that stabilize the power grid and improve the use of the energy that is recovered. These energy storage systems store energy and release it during acceleration of the train, reducing the load on the main power supply.

The use of regenerative braking energy can be divided into three main types: direct energy exchange between metro trains; energy transfer between the train and the energy storage system; energy exchange with a single power system. The overall energy efficiency in each case depends on both the amount of energy recovered and the number of energy conversion stages in the electric traction system.

A promising direction in the development of energy storage devices is the creation of combined two or three component storage devices, each of which has its own capacitive characteristic and dynamics of energy exchange with the network, which will allow increasing the energy efficiency of electric traction systems in the metro [3].

**Problem statement.** The purpose of the work is to conduct a comprehensive analysis of promising technologies for increasing the efficiency of the electric traction system of subways through the use of both promising types of equipment and optimization of the operating modes of the traction system elements.

**Research results.** Modern recuperation is not just a braking function, but a real-time intelligent energy management system that turns a decentralized fleet of trains into a virtual power plant.

Some of the promising technologies implemented in Europe and Asia are as follows:

Improved traction inverters with SiC and GaN transistors. As stated in [4] The basis of these technologies is the transition from traditional IGBT transistors to wide bandgap semiconductors (WBS) based on silicon carbide (SiC) and gallium nitride (GaN). Studies show that SiC transistors can reduce switching losses by up to 70 % compared to IGBTs, and also operate at significantly higher temperatures, which allows reducing the mass and volume of cooling systems by 50 % or more. The results of the implementation achieved the effect: the efficiency of the inverter converter increases from typical 93-95 % to 98-99.5 %. This is critically important for recovery, as it minimizes losses during two-way energy conversion (motor-generator). An example of the use of the approaches considered in Europe is the German concern Siemens Mobility in its Siemens platform Mireo Plus uses SiC power electronics, which is claimed to be a key factor in reducing power consumption by 25 % [5], in Asia, China's CRRC is integrating SiC modules into its latest trains, achieving a claimed 20-30 % increase in system efficiency [6].

The next direction of development of mutual energy management is the coordination of metro train movement with optimization of consumption and energy recovery for train traction (TOS). The basis of the technology is energy optimization algorithms that have become the subject of intensive scientific research, created on the basis of methods and models of predictive control (MPC – Model Predictive Control ), which allows dynamically calculating the movement profiles for all trains on the line simultaneously, maximizing the total recuperation and minimizing losses [7]. The following effect was achieved as a result. The systems allow raising the share of usefully used recuperative energy from the basic 30-40 % to 60-80 %, practically eliminating the discharge of energy into the braking resistors. An example of use is the TOS system from Siemens , deployed in the Nuremberg and London metro, which uses such algorithms [8] and JR East in Tokyo uses the Energy system Management [9].

Reversible traction substations and Smart energy districts. The basis of the technology is the introduction of bidirectional converters that allow the creation of DC microgrids based on the metro. Studies show that such systems can increase the energy sustainability of the city and reduce peak loads on the central grid [10]. The main effect of the implementation allows not only to use energy within one contact network, but also to export surpluses to the city grid. An example of application is the project of reversible substations in the Munich metro (Stadtwerke Munich and Siemens) [11] and Tokyo Metro and JR East use Toshiba reversing substations [12].

The evolution of the metro car from a passive energy consumer to an active node of the intelligent energy grid is the main path of development of the modern metro. A complex of technological means based on PMSM – SiC inverter – ESS forms the physical core of this transformation, and digital control systems are a component of the automated consumption, storage and recovery system. The implementation of these solutions leads to a significant increase in energy savings.

Modern energy storage systems (ESS) are the basis of the architecture of energy independence and grid stability. ESS solve the main problem of recovery – asynchrony of energy generation and consumption in space and time. Let's consider technological types, architectures and world examples. Stationary storage at substations (Wayside ESS). Let's consider the main technologies.

In [13], high-power lithium-ion batteries are considered. Research work focuses on optimizing the topology of battery connection to the DC network (DC/ DC converters) and developing charge/discharge management strategies to maximize battery life under frequent high-current operation (Barrero and al., 2020). An example of the use of the technology is the large-scale testing of Li-ion ESS in the Madrid metro by the EDDY consortium within the Shift2Rail program [14] and one of the world's largest Li-ion ESS for railways is installed in the Singapore metro ( Samsung SDI and Siemens ) [15].

An alternative approach is supercapacitor-based technology (EDLC). Studies [16] confirm their effectiveness for regenerative braking with ultra-short duration. Hybrid systems (supercapacitor + battery) are recognized as optimal in terms of cost, power and energy density [34]. An example of the use of supercapacitor storage technologies is Estonian Skeleton Technologies supplies ultracapacitors based on curved graphene for the Lisbon metro [17].

Currently, the following types of storage devices are most widely used in rolling stock: based on lithium-ion batteries [18, 19], based on double-layer capacitors [20, 21], and based on flywheels [22].

In the laboratory of the Japan Railway Research Institute, a tram car weighing 19.7 tons with two asynchronous traction motors with a capacity of 60 kW was tested with an acceleration of 3 km/h/s and a deceleration of 3.4 km/h/s with an onboard letter 1.2, the technical characteristics of which are given in tab. 1.

The studies showed that the amount of energy consumed by the tram for acceleration was 3214.7 kJ. When the tram is braked from a speed of 49.9 km/h , the kinetic energy is 2085.1 kJ. The amount of energy recovered is 1535.8 kJ. As a result, the amount of energy consumed during the running tests was 1678.9 kJ. Thus, the recovery ratio for acceleration was 47.8 %, and for braking – 73.7 %.

Lithium-ion battery-based storage devices have the following disadvantages [23]:

- Inadmissibility of overheating by operating current;
- Narrow temperature range of operation, especially at negative temperatures;
- The impact of aging on the quality of performance;
- The need for complex, bulky switching and control systems;
- High cost today.

Another type of storage device is based on the use of double-layer capacitors as batteries. An experimental storage device based on double-layer capacitors was created in the power supply laboratory of the Japan Railway Research Institute [21], the performance of which is given in tab. 2.

Table 1 – Battery specifications

| Parameter | Value |
|---|---|
| Capacity, A h | 55 |
| High-voltage , | 604.8 (3.6 V x 168 cells) |
| Maximum charge voltage, | 705.6 |
| Minimum discharge voltage, | 504.0 |
| Maximum current, A | 500 |
| Size, mm | W960 x H1000X D900 (84 cells) x 2 |
| Weight, kg | 580 (84 cells) x2 (including frame) |

Table 2 – Technical characteristics of a double-layer capacitor storage device

| Parameter | Value | | |
|---|---|---|---|
| Element | Cells | Bloc | Module |
| Composition | 8 cells successively | 8 cells successively | 3 blocks successively |
| Voltage, V | 93 | 93 | 280 |
| Current, A | 50 | 400 | 400 |
| Capacity, F | 14 | 97 | 32 |
| Resistance, Ohm | 0.44 | 0.05 | 0.16 |
| Dimensions, DxWxH , mm | 340x340x50 | 431x465x537 | 1000x900x2300 |
| Weight, kg | 7.2 | 74.5 | 715 |

Storage devices based on double-layer capacitors have the following disadvantages [23] – inability to use the full energy of capacitors due to the linearity of the discharge voltage;

In addition to stationary energy storage systems, it is possible to use onboard storage systems on cars (On-board ESS). The basis of this approach is the technology based on Lithium-titanate (LTO) batteries are actively researched for rail transport due to their outstanding cyclicity (>20,000 cycles) and safety. In work [24], scientists propose integrating such storage systems into the car power supply system to implement contactless movement on neutral inserts. A practical implementation is the Chinese CRRC mass-producing metro cars with onboard LTO storage systems [25].

Increasing energy efficiency in traction drive through the use of permanent magnet synchronous motors (PMSM). PMSMs are a combination of reactive induction motor technology and permanent magnet synchronous motors. In order to achieve the possibility of mass production of PMSM motors, design and subsequent technological innovations have been introduced.

In materials science and production of high-energy magnets, a technology has been introduced that aims to reduce the dependence on dysprosium (Dy) while maintaining the thermal stability of NdFeB magnets. The use of grain boundary diffusion technology (GND) Boundary Diffusion allows for a significant reduction in the dysprosium content while maintaining high coercivity [26].

Innovative designs of traction electric motors allow the use of gearless motor-wheel technology (Direct Drive). Comparative studies confirm that gearless PMSM-based drives provide an increase in the overall efficiency of the traction drive by 5-7 % by eliminating losses in the gearbox, as well as reducing weight and maintenance [27]. Current examples of applications are CRRC Zhuzhou Electric Locomotive Institute is a world leader in the commercialization of motor wheels for subways [28].

Another technological advancement is the use of liquid-cooled PMSM motors. Developments are aimed at integrating cooling systems into the motor housing, which allows for increased energy loads in structural elements and reduced mass of active materials and overall size of the traction drive. An example of application is Siemens Mobility uses compact liquid-cooled PMSMs in Inspiro trains [29].

An important direction of development of modern technologies for increasing energy efficiency are traction motor control systems with simultaneous control of permanent magnet demagnetization. Research conducted in [30] shows that the most vulnerable element of PMSM traction motor design in terms of temperature load is permanent magnets. To protect PMSM from irreversible demagnetization during overheating, advanced observers and algorithms are being developed that estimate the temperature of the magnets in real time and limit the stator current, preventing loss of performance.

Permanent magnet synchronous reluctance motors are one of the most efficient categories of electric machines used in modern transportation systems. Their high efficiency significantly reduces electricity consumption and provides a longer range on a single battery charge, which is especially important for electric vehicles. One of the key advantages of PMSMs compared to other types of electric motors is their ability to maintain high efficiency over a wide speed range. In addition, these motors are characterized by a relatively simple design and lower overall weight, which further increases their suitability for traction applications [32, 33].

The high efficiency of PMSMs is largely due to their improved power factor, which reduces the effect of static losses in the stator windings. Moreover, unlike conventional induction motors, PMSMs do not suffer from magnetic flux leakage associated with rotor currents. In induction machines, such leakage leads to additional losses and a corresponding decrease in overall efficiency. Since PMSMs are widely used in electric vehicles, such as electric buses and other types of electric transport, where efficiency is a critical parameter, their use contributes to reducing the operating costs of electricity [34,35].

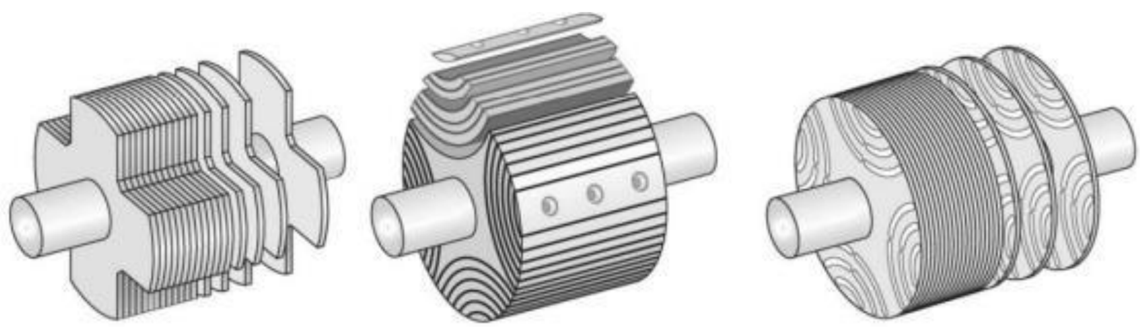
In PMSM motors, most of the electromagnetic torque is generated by the interaction between the magnetic field generated by the permanent magnets on the rotor and the rotating magnetic field generated by the stator currents. However, torque generation is also strongly affected by structural asymmetry within the machine. Such asymmetry can arise from uneven placement of rotor components, such as rotor fins, or from uneven distribution of permanent magnets. The combined effect of the magnetic moment and the reactive moment resulting from this asymmetry allows PMSMs to achieve high torque densities while maintaining efficient operation.

The rotor design plays a crucial role in determining the performance of synchronous machines based on the non-uniformity of the magnetic resistance in the rotor. One of the simplest rotor configurations is the salient-pole rotor. In this design, the permanent magnets are mounted on the rotor surface and protrude towards the stator. This arrangement is relatively easy to manufacture and provides a simple magnetic circuit, making it suitable for certain applications where simplicity and cost are priorities [34, 35].

Another advanced rotor configuration is the axial laminated anisotropy (ALA) rotor. This type of rotor consists of thin laminated sheets whose magnetic orientation is aligned along the rotor axis. This structure, illustrated in Fig. 1 b, provides a high magnetic flux density on the rotor surface. As a result, the output torque is increased and the energy losses associated with magnetization reversal are reduced. This rotor concept has been successfully implemented in traction motors manufactured by Siemens, as shown in fig. 2, demonstrating its effectiveness in high-performance electric drive systems.

A further development is the multi-layer anisotropy (TLA) rotor design. This rotor consists of several layers of laminated sheets, each with a magnetic orientation located in different directions, as shown in Fig. 1c. This layered configuration enhances the magnetic anisotropy and allows for optimal control of the magnetic flux paths inside the rotor. Consequently, the rotor achieves a high surface magnetic density, which leads to increased torque and reduced magnetization losses. Such designs are particularly advantageous for high-efficiency traction motors operating under demanding load and speed conditions.

A transverse anisotropy layer (TLA) rotor consists of multiple laminated layers with magnetic orientations arranged in different directions, as shown in Fig. 1c. This structure also results in a high surface magnetic flux density, which results in increased torque and reduced energy loss during magnetization reversal.



a) b) c)

Fig. 1 − Types of rotor designs for synchronous jet motors:
a) rotor with a single salient pole, b) ALA rotor, c) TLA rotor

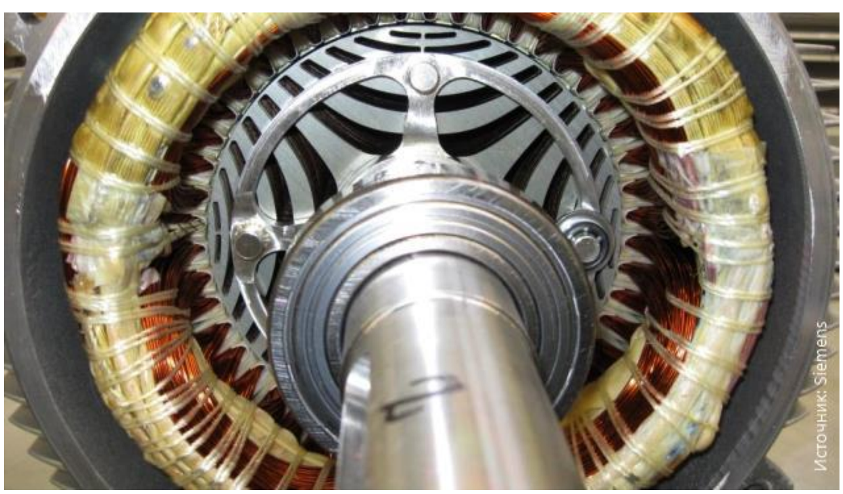



Fig. 2 – Siemens synchronous jet engine

In PMSM designs, the rotor typically contains permanent magnets mounted on its surface, often using anisotropic layers (ALA or TLA). Such rotor configurations provide high magnetic flux density on the surface, minimizing energy losses associated with magnetization reversal.

As a result, the TLA rotor has become a popular choice for PMSMs. Its design is complex, with anisotropic steel plates oriented at different angles to the rotor magnets. This arrangement reduces energy dissipation in the rotor and increases overall motor efficiency. In addition, TLA rotors offer higher specific strength, allowing them to operate at higher speeds with minimal vibration and noise – a beneficial characteristic for electric vehicles and other demanding applications where strength and reliability are critical.

The complex process of operation of the promising electric traction system of the metro involves the following components of the time diagram of operation.

1. A metro car with a PMSM-based traction drive approaches a station. The on-board computer, having received data from the central ATO dispatcher, calculates the optimal braking start point and brake operating modes.

2. The PMSM motor switches to generator mode. Thanks to high efficiency and precise control, 95 % of the kinetic energy is converted into electrical energy.

3. A low-loss SiC inverter directs this energy to the overhead contact line. Some of it is instantly consumed by a nearby accelerating train, also equipped with a PMSM.

4. Excess energy not consumed in the network is captured in a split second by the on-board supercapacitor module or fed to a stationary Li-ion ESS at the nearest substation.

5. The central energy management system (EMS), analyzing the schedule of all trains, decides when and where to discharge the storage batteries: to power the accelerating train, to return to the city network through a reversing substation, or to supply station equipment.

6. The entire data chain (energy flows, train positions, storage status) is collected and analyzed in a digital twin (Digital Twin) of the metro, which allows for continuous training and improvement of optimization algorithms.

An example of the application of such technologies is the global integrated projects

«European Rail Energy Storage System» (EU-Rail ESS): Within the framework of the Europe's Rail initiative aims to standardize and implement hybrid ESS (supercapacitors + batteries) combined with PMSM motors to create a new generation of rolling stock with zero energy emissions in braking resistors, as well as the Japanese initiative «Smart Railway System»: JR East and Toshiba are developing comprehensive systems where PMSM, recuperation, ESS and hydrogen fuel cells are integrated to create fully energy-autonomous railway lines.

**Conclusions.** The introduction of energy-efficient systems in metro rolling stock can significantly reduce traction electricity consumption – up to 40 % using recuperation systems and another 10-20 % using energy storage systems. Microprocessor control systems can also help reduce electricity consumption by 10 %. The introduction of such systems is a promising direction for energy saving in metro rolling stock and has lower capital investments. They can be installed on various types of rolling stock and will help improve traffic safety, stabilize the traffic schedule and make train control easier for drivers.

**БІБЛІОГРАФІЧНИЙ СПИСОК:**


1. Su S., Li X., Tang T., Gao Z. Y. (2013). A subway train timetable optimization approach based on energy-efficient operation strategy. *IEEE Transactions on Intelligent Transportation* Systems, 14(2), 883–893. https://doi.org/10.1109/TITS.2013.2246190
2. Su S., Tang T., Li X., Gao Z. Y. (2014). Optimization on multitrain operation in subway system. *IEEE Transactions on Intelligent Transportation Systems*, 15(2), 673–684. https://doi.org/10.1109/TITS.2013.2289332
3. Goolak S., Kondratieva L., Riabov I., Keršys A., Makaras R. (2023). Research and optimization of hybrid on-board energy storage system of an electric locomotive for quarry rail transport. *Energies*, 16(7), Article 3293. https://doi.org/10.3390/en16073293
4. Rohani A., Lee F. C. (2019). Design considerations for high-efficiency power converters using wide-bandgap devices. *IEEE Transactions on Power Electronics*, 34(6), 5895–5907. https://doi.org/10.1109/TPEL.2019.2897063
5. Siemens AG. (2021, May 18). *Siemens presents Mireo Plus platform for sustainable rail transport* [Press release]. https://www.mobility.siemens.com/global/en/portfolio/rolling-stock/commuter-and-regional-trains/mireo/mireo-plus.html
6. CRRC Corporation Limited. (2022). *Application of SiC power modules in rail transit*. https://www.crrcgc.cc/en/g7389/s12350/t312237.aspx
7. Yang X., Li X., Ning B., Tang T. (2016). A survey on energy-efficient train operation for urban rail transit. *IEEE Transactions on Intelligent Transportation Systems*, 17(1), 2–13. https://doi.org/10.1109/TITS.2015.2447507

8. Siemens Mobility. (2023). *Train operation solutions (TOS)*. https://www.mobility.siemens.com/global/en/portfolio/rail/automation/railway-automation/train-operations-solutions.html

9. East Japan Railway Company. (2022). *Energy management ATO system*. https://www.jreast.co.jp/e/development/tech/energy_management.html

10. Brenna M., Foiadelli F., Zaninelli D. (2018). *Electrical railway transportation systems*. IEEE Press.

11. Siemens AG. (n.d.). *Reversible substations for Munich's subways*. https://press.siemens.com/global/en/pressrelease/reversible-substations-munichs-subways

12. Toshiba Corporation. (n.d.). *Energy systems*. https://www.global.toshiba/ww/company/energy.html

13. Barrero R., Tackoen X., Van Mierlo J. (2010). Stationary or onboard energy storage systems for energy consumption reduction in a metro network. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(3), 207–225. https://doi.org/10.1243/09544097JRRT292

14. Shift2Rail Joint Undertaking. (n.d.). *EDDY project*. https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=EDDY

15. Siemens AG. (n.d.). *Siemens and Samsung SDI provide one of the world's most powerful battery storage systems*. https://press.siemens.com/global/en/pressrelease/siemens-and-samsung-sdi-provide-one-worlds-most-powerful-battery-storage-systems

16. Iannuzzi D., Tricoli P. (2012). Speed-based state-of-charge tracking control for metro trains with onboard supercapacitors. *IEEE Transactions on Power Electronics*, 27(4), 2129–2140. https://doi.org/10.1109/TPEL.2011.2167633

17. Skeleton Technologies. (n.d.). *Skeleton supplies ultracapacitors for Lisbon metro energy efficiency project*. https://www.skeletontech.com/press-releases/skeleton-supplies-ultracapacitors-for-lisbon-metro-energy-efficiency-project

18. Okazaki K., Nishiyama K., Yamano Y. (2002). Feasibility study of the power storage system by using lithium-ion batteries for the electric railway. *IEE Japan Technical Report* (TER-02-34), 31–36.

19. Taguchi Y., Ogasa M. (2013). SOC estimation method of lithium-ion battery for contact wire and battery hybrid electric railway vehicle. *Quarterly Report of RTRI*, 54(3), 145–151.

20. Doki T., Takahara E., Yamada J. (2003). A study for electric double layer capacitor series connection for railway traction. In *Proceedings of the IEE Japan Industry Applications Society Conference* (Vol. 3, pp. 179–182).

21. Konishi, T., & Nakamichi, Y. (2004). Energy storage system for DC electrified railway using EDLC. *Quarterly Report of RTRI, 45*(2), 53–58.

22. Kawaguchi K., Ogasa M., Kondou H., Takakado Y., Matsumura H. (2003). Epitome of sliding bearing type of flywheel energy storage equipment for hybrid vehicle. In *Proceedings of the IEE Japan Industry Applications Society Conference* (Vol. 2, pp. 523–526).

23. Овер'янова Л. В. (2012). Електромеханічний перетворювач інерційного накопичувача енергії для електрорухомого складу приміського сполучення. *Вісник Національного технічного університету «Харківський політехнічний інститут»*, (20), 84–90.

24. Liu X., Li K. (2020). Energy storage devices in electrified railway systems: A review. *Transportation Safety and Environment*, 2, Article tdaa016. https://doi.org/10.1093/tse/tdaa016

25. Shtompel O., Khvorost M. (2025). Determination of the energy-optimal trajectory of a metro car based on solving a conditional minimization problem. *Energy Saving. Power Engineering. Energy Audit*, 9(212), 57–73. https://doi.org/10.20998/2313-8890.2025.09.05

26. Sasaki T. T., Ohkubo T., Hono K. (2016). Structure and chemical compositions of the grain boundary phase in Nd–Fe–B sintered magnets. *Acta Materialia*, 115, 269–277. https://doi.org/10.1016/j.actamat.2016.05.035

27. Vlachou V. I., Sakkas G. K., Xintaropoulos F. P., Pechlivanidou M. S. C., Kefalas T. D., Tsili M. A., Kladas A. G. (2023). Overview on permanent magnet motor trends and developments. *Preprints*. https://doi.org/10.20944/preprints202312.1678.v1

28. Штомпель О. М., Любарський Б. Г. (2024). Аналіз перспективних технологій підвищення енергоефективності в системі енергозабезпечення. У *Інформаційні технології: наука, техніка, технологія, освіта, здоров'я: тези доповідей XXXII міжнародної науково-практичної конференції MicroCAD-2024* (с. 96). НТУ «ХПІ».

29. Siemens Mobility. (n.d.). *Siemens Mobility to supply Inspiro trains for Warsaw metro*. https://press.siemens.com/global/en/pressrelease/siemens-mobility-supply-24-inspiro-trains-warsaw-metro

30. Zhang C., Wu G., He J., Feng J., Zhao K. (2017). Fault-tolerant predictive control for demagnetization faults in permanent magnet synchronous machine. *Transactions of China Electrotechnical Society*, 32, 100–110. https://doi.org/10.19595/j.cnki.1000-6753.tces.L70059

31. Bu B., Qin G., Li L., Li G. (2018). An energy efficient train dispatch and control integrated method in urban rail transit. *Energies*, 11(5), Article 1248. https://doi.org/10.3390/en11051248

32. Liubarskyi B., Iakunin D., Nikonov O., Liubarskyi D., Yeritsyan B. (2022). Optimizing geometric parameters for the rotor of a traction synchronous reluctance motor assisted by partitioned permanent magnets. *Eastern-European Journal of Enterprise Technologies*, 2(8(116)), 38–44. https://doi.org/10.15587/1729-4061.2022.254373

33. Liubarskyi B., Iakunin D., Nikonov O., Liubarskyi D., Vasenko V., Gasanov M. (2021). Procedure for selecting optimal geometric parameters of the rotor for a traction non-partitioned permanent magnet-assisted synchronous reluctance motor. *Eastern-European Journal of Enterprise Technologies*, 6(8(114)), 27–33. https://doi.org/10.15587/1729-4061.2021.247208

34. Stipetic S., Zarko D., Kovacic M. (2016). Optimised design of permanent magnet assisted synchronous reluctance motor series using combined analytical–finite element analysis based approach. *IET Electric Power Applications*, 10(5), 330–338. https://doi.org/10.1049/iet-epa.2015.0341

35. Trancho E., Ibarra E., Arias A., Kortabarria I., Jurgens J., Marengo L., Fricasse A., Gragger J. (n.d.). PM-assisted synchronous reluctance machine flux weakening control for EV and HEV applications. *IEEE Transactions on Industrial Electronics*.

## REFERENCES:

1. Su S., Li X., Tang T., Gao Z. Y. (2013). A subway train timetable optimization approach based on energy-efficient operation strategy. *IEEE Transactions on Intelligent Transportation* Systems, 14(2), 883–893. https://doi.org/10.1109/TITS.2013.2246190

2. Su S., Tang T., Li X., Gao Z. Y. (2014). Optimization on multitrain operation in subway system. *IEEE Transactions on Intelligent Transportation Systems*, 15(2), 673–684. https://doi.org/10.1109/TITS.2013.2289332

3. Goolak S., Kondratieva L., Riabov I., Keršys A., Makaras R. (2023). Research and optimization of hybrid on-board energy storage system of an electric locomotive for quarry rail transport. *Energies*, 16(7), Article 3293. https://doi.org/10.3390/en16073293

4. Rohani A., Lee F. C. (2019). Design considerations for high-efficiency power converters using wide-bandgap devices. *IEEE Transactions on Power Electronics*, 34(6), 5895–5907. https://doi.org/10.1109/TPEL.2019.2897063

5. Siemens AG. (2021, May 18). *Siemens presents Mireo Plus platform for sustainable rail transport* [Press release]. https://www.mobility.siemens.com/global/en/portfolio/rolling-stock/commuter-and-regional-trains/mireo/mireo-plus.html

6. CRRC Corporation Limited. (2022). *Application of SiC power modules in rail transit*. https://www.crrcgc.cc/en/g7389/s12350/t312237.aspx

7. Yang X., Li X., Ning B., Tang T. (2016). A survey on energy-efficient train operation for urban rail transit. *IEEE Transactions on Intelligent Transportation Systems*, 17(1), 2–13. https://doi.org/10.1109/TITS.2015.2447507

8. Siemens Mobility. (2023). *Train operation solutions (TOS)*. https://www.mobility.siemens.com/global/en/portfolio/rail/automation/railway-automation/train-operations-solutions.html

9. East Japan Railway Company. (2022). *Energy management ATO system*. https://www.jreast.co.jp/e/development/tech/energy_management.html

10. Brenna M., Foiadelli F., Zaninelli D. (2018). *Electrical railway transportation systems*. IEEE Press.

11. Siemens AG. (n.d.). *Reversible substations for Munich's subways*. https://press.siemens.com/global/en/pressrelease/reversible-substations-munichs-subways

12. Toshiba Corporation. (n.d.). *Energy systems*. https://www.global.toshiba/ww/company/energy.html

13. Barrero R., Tackoen X., Van Mierlo J. (2010). Stationary or onboard energy storage systems for energy consumption reduction in a metro network. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(3), 207–225. https://doi.org/10.1243/09544097JRRT292

14. Shift2Rail Joint Undertaking. (n.d.). *EDDY project*. https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=EDDY

15. Siemens AG. (n.d.). *Siemens and Samsung SDI provide one of the world's most powerful battery storage systems*. https://press.siemens.com/global/en/pressrelease/siemens-and-samsung-sdi-provide-one-worlds-most-powerful-battery-storage-systems

16. Iannuzzi D., Tricoli P. (2012). Speed-based state-of-charge tracking control for metro trains with onboard supercapacitors. *IEEE Transactions on Power Electronics*, 27(4), 2129–2140. https://doi.org/10.1109/TPEL.2011.2167633

17. Skeleton Technologies. (n.d.). *Skeleton supplies ultracapacitors for Lisbon metro energy efficiency project*. https://www.skeletontech.com/press-releases/skeleton-supplies-ultracapacitors-for-lisbon-metro-energy-efficiency-project

18. Okazaki K., Nishiyama K., Yamano Y. (2002). Feasibility study of the power storage system by using lithium-ion batteries for the electric railway. *IEE Japan Technical Report* (TER-02-34), 31–36.

19. Taguchi Y., Ogasa M. (2013). SOC estimation method of lithium-ion battery for contact wire and battery hybrid electric railway vehicle. *Quarterly Report of RTRI*, 54(3), 145–151.

20. Doki T., Takahara E., Yamada J. (2003). A study for electric double layer capacitor series connection for railway traction. In *Proceedings of the IEE Japan Industry Applications Society Conference* (Vol. 3, pp. 179–182).

21. Konishi, T., & Nakamichi, Y. (2004). Energy storage system for DC electrified railway using EDLC. *Quarterly Report of RTRI*, *45*(2), 53–58.

22. Kawaguchi K., Ogasa M., Kondou H., Takakado Y., Matsumura H. (2003). Epitome of sliding bearing type of flywheel energy storage equipment for hybrid vehicle. In *Proceedings of the IEE Japan Industry Applications Society Conference* (Vol. 2, pp. 523–526).

23. Overianova, L. V. (2012). *Elektromekhanichnyi peretvoriuvach inertsiinoho nakopychuvacha enerhii dlia elektrorukhomoho skladu prymiskoho spoluchennia*. *Visnyk Natsionalnoho tekhnichnoho universytetu "Kharkivskyi politekhnichnyi instytut"*, (20), 84–90.

24. Liu X., Li K. (2020). Energy storage devices in electrified railway systems: A review. *Transportation Safety and Environment*, 2, Article tdaa016. https://doi.org/10.1093/tse/tdaa016

25. Shtompel O., Khvorost M. (2025). Determination of the energy-optimal trajectory of a metro car based on solving a conditional minimization problem. *Energy Saving. Power Engineering. Energy Audit*, 9(212), 57–73. https://doi.org/10.20998/2313-8890.2025.09.05

26. Sasaki T. T., Ohkubo T., Hono K. (2016). Structure and chemical compositions of the grain boundary phase in Nd–Fe–B sintered magnets. *Acta Materialia*, 115, 269–277. https://doi.org/10.1016/j.actamat.2016.05.035

27. Vlachou V. I., Sakkas G. K., Xintaropoulos F. P., Pechlivanidou M. S. C., Kefalas T. D., Tsili M. A., Kladas A. G. (2023). Overview on permanent magnet motor trends and developments. *Preprints*. https://doi.org/10.20944/preprints202312.1678.v1

28. Siemens Mobility. (n.d.). *Siemens Mobility to supply Inspiro trains for Warsaw metro*. https://press.siemens.com/global/en/pressrelease/siemens-mobility-supply-24-inspiro-trains-warsaw-metro

29. Siemens Mobility. (n.d.). *Siemens Mobility to supply Inspiro trains for Warsaw metro*. https://press.siemens.com/global/en/pressrelease/siemens-mobility-supply-24-inspiro-trains-warsaw-metro

30. Zhang C., Wu G., He J., Feng J., Zhao K. (2017). Fault-tolerant predictive control for demagnetization faults in permanent magnet synchronous machine. *Transactions of China Electrotechnical Society*, 32, 100–110. https://doi.org/10.19595/j.cnki.1000-6753.tces.L70059

31. Bu B., Qin G., Li L., Li G. (2018). An energy efficient train dispatch and control integrated method in urban rail transit. *Energies*, 11(5), Article 1248. https://doi.org/10.3390/en11051248

32. Liubarskyi B., Iakunin D., Nikonov O., Liubarskyi D., Yeritsyan B. (2022). Optimizing geometric parameters for the rotor of a traction synchronous reluctance motor assisted by partitioned permanent magnets. *Eastern-European Journal of Enterprise Technologies*, 2(8(116)), 38–44. https://doi.org/10.15587/1729-4061.2022.254373

33. Liubarskyi B., Iakunin D., Nikonov O., Liubarskyi D., Vasenko V., Gasanov M. (2021). Procedure for selecting optimal geometric parameters of the rotor for a traction non-partitioned permanent magnet-assisted synchronous reluctance motor. *Eastern-European Journal of Enterprise Technologies*, 6(8(114)), 27–33. https://doi.org/10.15587/1729-4061.2021.247208

34. Stipetic S., Zarko D., Kovacic M. (2016). Optimised design of permanent magnet assisted synchronous reluctance motor series using combined analytical–finite element analysis based approach. *IET Electric Power Applications*, 10(5), 330–338. https://doi.org/10.1049/iet-epa.2015.0341

35. Trancho E., Ibarra E., Arias A., Kortabarria I., Jurgens J., Marengo L., Fricasse A., Gragger J. (n.d.). PM-assisted synchronous reluctance machine flux weakening control for EV and HEV applications. *IEEE Transactions on Industrial Electronics*.

*Стаття надійшла до редакції: 18.10.2025; рецензування: 28.10.2025;*
*прийнята до публікації 02.11.2025. Автори прочитали и дали згоду рукопису.*
*The article was submitted on 18.10.2025; revised on 28.10.2025; and accepted for publication on 02.11.2025. The authors read and approved the final version of the manuscript.*