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INNOVATIONS AND STANDARDIZATION OF ELECTRICAL EQUIPMENT OF ELECTRIC VEHICLES FOR TECHNICAL UNIFICATION AND ENERGY EFFICIENCY

Н. Ореховська, Ю. Шихірева. **Інновації та стандартизація електрообладнання електромобілів для технічної уніфікації та енергоефективності.** Стаття присвячена аналізу проблем і перспектив стандартизації електрообладнання електромобілів, що забезпечує технічну сумісність, енергоефективність і зниження собівартості виробництва. Досліджено міжнародні стандарти, які регулюють системи живлення, зарядну інфраструктуру, протоколи зв'язку та захист від кібератак. Основними викликами є регіональні відмінності в стандартах, різноманітність протоколів зв'язку, вразливості до кіберзагроз і фрагментація технологій бездротової зарядки. У контексті України обмежена інфраструктура зарядних станцій, воєнні ризики та пільги на імпорт компонентів створюють унікальні можливості для розвитку локального виробництва. Запропоновано підходи до гармонізації стандартів, зокрема впровадження єдиних технічних вимог і технологій взаємодії транспортних засобів із електромережею, що сприяють інтеграції штучного інтелекту для оптимізації зарядки. Уніфікація стандартів може знизити собівартість виробництва електрообладнання на 15–20%, підвищити енергоефективність і розширити доступність зарядної інфраструктури. В Україні гармонізація стандартів сприятиме залученню інвестицій, розвитку сталого ринку електромобілів і покращенню споживчого сприйняття. Перспективи включають створення єдиної мережі зарядних станцій, сумісної з міжнародними стандартами, що стимулюватиме зростання електромобільної галузі та інтеграцію з європейськими ринками. Стаття підкреслює необхідність співпраці між виробниками, урядом і міжнародними організаціями для подолання технічних і ринкових бар'єрів, що є ключовим для масштабування електромобільності в Україні та світі.

Ключові слова: електромобільність, стандартизація, уніфікація, електрообладнання, зарядна інфраструктура, енергоефективність, кібербезпека, локальне виробництво, ринок електромобілів, гармонізація стандартів

N. Orekhovska, Y. Shikhireva. **Innovations and standardization of electrical equipment of electric vehicles for technical unification and energy efficiency.** The article is devoted to the analysis of the problems and prospects of standardization of electrical equipment of electric vehicles, which ensures technical compatibility, energy efficiency and reduction of production costs. International standards regulating power systems, charging infrastructure, communication protocols and protection against cyberattacks are studied. The main challenges are regional differences in standards, diversity of communication protocols, vulnerabilities to cyber threats and fragmentation of wireless charging technologies. In the context of Ukraine, the limited infrastructure of charging stations, military risks and privileges for the import of components create unique opportunities for the development of local production. Approaches to harmonization of standards are proposed, in particular, the introduction of unified technical requirements and technologies for interaction of vehicles with the power grid, which contribute to the integration of artificial intelligence for charging optimization. Unification of standards can reduce the cost of production of electrical equipment by 15–20%, increase energy efficiency and expand the availability of charging infrastructure. In Ukraine, harmonization of standards will help attract investment, develop a sustainable electric vehicle market, and improve consumer acceptance. Prospects include the creation of a single network of charging stations compatible with international standards, which will stimulate the growth of the electric vehicle industry and integration with European markets. The article emphasizes the need for cooperation between manufacturers, the government, and international organizations to overcome technical and market barriers, which is key to scaling up electric mobility in Ukraine and the world.

Keywords: electric mobility, standardization, unification, electrical equipment, charging infrastructure, energy efficiency, cybersecurity, local production, electric vehicle market, harmonization of standards

Introduction

In the current conditions of rapid development of the electric vehicle industry, where sales of electric vehicles are growing by 40% annually [1], the issue of unification of electrical equipment is becoming particularly relevant. The reliability and safety of vehicles, as well as the pace of their mass introduction into global practice, depend on the unity of technical solutions, standards, and approaches to electric motors, inverters, batteries, and charging infrastructure. Unification is a key factor determining the efficiency of production, service, and integration of the latest technologies, such as intelligent control systems. At the same time, the existence of various standards (SAE, IEC, GB/T) among leading automotive companies creates significant barriers. Differences in the design of electronic units, power supply systems, communication protocols, and diagnostic methods complicate the ex-

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change of technologies, increase costs, and hinder the formation of a single global market. This diversity of standards is one of the main challenges facing the modern electric vehicle industry.

Analysis of literature data and problem statement

The main idea of the article is that the standardization of electric vehicle equipment, including batteries, electric motors, inverters, control systems, and charging infrastructure, is a critical factor in ensuring energy efficiency, reducing production costs by 15–20%, [1], and accelerating the global adoption of electric vehicles.

The unification of standards such as SAE J3400 (NACS), IEC 62196, and ISO 15118 allows regional barriers to be overcome, ensures the compatibility of electromechanical components, and optimizes the integration of innovative technologies such as V2G (Vehicle-to-Grid – two-way energy exchange between an electric vehicle and the power grid) and AI-based diagnostic systems (Artificial Intelligence) [2, 3].

At the same time, the Ukrainian context, in particular the limited charging infrastructure and local production, emphasizes the need to adapt international standards to support the development of the electric vehicle industry in Ukraine [4]. The article emphasizes that overcoming technical, economic, and market barriers through unification will contribute to the creation of a sustainable and competitive global electric vehicle market.

The issues of standardization and development of charging infrastructure for electric vehicles are key in contemporary research in the fields of electric power engineering, electrical engineering, and marketing, as they affect the energy efficiency, cost, and market attractiveness of electric vehicles.

In recent years, scientific publications, technical reports, and government documents have actively highlighted the issues of standardization, integration of charging stations with power grids, and marketing strategies for promoting electric mobility, particularly in the Ukrainian context.

Wajdi W. and Chakir A. [2] analyze charging standards (IEC 61851, IEC 62196) and their impact on integration with power grids, emphasizing that the unification of connectors and communication protocols (OCPP, ISO 15118) reduces infrastructure costs by 10–15% and increases its accessibility.

Kakkar R. et al. [5] propose a detailed taxonomy of charging standards (SAE J1772, CHAdeMO, CCS) and technologies (wired and wireless charging), emphasizing the need for standardization to reduce infrastructure deployment costs and ensure compatibility for different types of vehicles (2W, 3W, 4W). They also propose an architecture for public charging stations that can be adapted to Ukrainian realities to increase market appeal.

Funke, S.Á. et al. [6] emphasize that the incompatibility between CCS and CHAdeMO complicates the marketing of electric vehicles due to infrastructure fragmentation, increasing costs by 10–20% and causing confusion among consumers.

International sources, such as the US Department of Transportation report [7] and the ICC roadmap [8], emphasize SAE J3400 (NACS) and ISO 15118 standards for V2G technologies, which promote energy efficiency and reduce logistics costs by 20% in rural areas.

Lieven T. [9] notes that unified standards contribute to a 15-20% reduction in costs, while import incentives and subsidies increase the market appeal of electric vehicles by reducing barriers for consumers.

Ukrainian scientists Davydov V.O. and Stafidov E.B. [3] propose integrating V2G through unified protocols for balancing energy systems, which reduces peak loads by 10–15% and maintains energy stability in conditions of military risk.

O.V. Stetsyuk et al. [10] emphasize that preferential taxation and standardization of charging systems contribute to the growth of the electric vehicle market in Ukraine, but military risks complicate infrastructure development, which affects consumer perception.

Zakharchenko Yu.V. et al. [4] propose marketing strategies based on standardization and integration with power systems to increase the competitiveness of local companies and attract consumers by simplifying access to charging.

Rick Lezman [11] emphasizes the importance of standardizing charging infrastructure for electric vehicles, highlighting the progress of the SAE J3400 (NACS) standard. The adoption of J3400 as a recommended practice in 2024 promotes the compatibility of charging systems, reducing market barriers and increasing convenience for consumers. The transition of leading automakers (Ford, GM, Volvo) to NACS, which prevails over CCS, expands access to charging stations, which is key to the growth of the electric vehicle market.

This echoes the work of Stetsyuk O.V. et al. and Zakharchenko Y.V. et al., who note that such unification could eliminate confusion for consumers, increase market appeal, and support infrastructure development despite the challenges of war.

National standards and requirements for electric vehicle infrastructure, in particular the final rule [12], establish mandatory standards for charging infrastructure in the US, promoting unification and increasing the availability of charging stations. These standards can be adapted in Ukraine to attract investment and expand the charging network.

Thus, the literature confirms that standardization of charging infrastructure and electrical equipment is key to reducing costs and improving energy efficiency. The unification of standards (IEC 62196 [13], ISO 15118 [14], SAE J3400 [15]) reduces technical, economic, and market barriers, promoting the sustainable development of electromobility. In Ukraine, the adaptation of these standards is critical to overcoming infrastructure constraints and promoting electric vehicles through consumer-oriented marketing initiatives.

Purpose and objectives of the study

The purpose of this study is to analyze the problems and prospects of unifying electric vehicle electrical equipment in the context of global and Ukrainian trends in the automotive industry, as well as to develop recommendations for harmonizing standards to support local production and integration with power systems. The objective of the study is to analyze existing approaches to standardization, identify factors that hinder unification, and formulate ways to overcome them.

Research materials and methods

A comprehensive approach was used to study the standardization of electric vehicle electrical equipment. An analysis of scientific literature, technical documentation, international standards, and government reports was conducted to identify trends and challenges in unification. A comparative analysis of standards assessed the barriers to compatibility between charging infrastructure and power systems. A critical analysis of local studies identified problems with integration with power systems. Data synthesis contributed to the formation of proposals for harmonizing standards and introducing innovations. Quantitative analysis of technical characteristics assessed the impact of unification on energy efficiency and cost.

Scientific novelty

The scientific novelty of the article lies in the development of specific approaches to harmonizing standards for electric vehicle electrical equipment, adapted to the conditions of Ukraine, in particular through the integration of the CCS2 standard with local privileges for the import of components, which can reduce production costs by 15–20%. The proposal for modular charging systems compatible with CCS, CHAdeMO, and GB/T, using IEC 61851-21-2 to ensure electromagnetic compatibility, is an original contribution to overcoming regional fragmentation. A quantitative assessment of the effect of implementing ISO 15118 for V2G technologies, which can reduce peak loads on Ukraine's power systems by 10…15%, adds practical value. In addition, the integration of AI for adaptive battery temperature control with unified protocols, in particular ISO 19363 for wireless charging, represents an innovative approach that takes into account military risks and limited infrastructure, creating a basis for the further development of local electric vehicle production.

Research results

Standardization in the automotive industry is the process of establishing uniform technical requirements, rules, and standards for components, systems, and processes to ensure compatibility, safety, and production efficiency. Unification, as a component of standardization, involves the creation of universal solutions for electrical equipment (e.g., batteries, electric motors, inverters, and charging infrastructure), which reduces the variety of options and facilitates the integration of components from different manufacturers. In the context of electric vehicles, standardization and unification are aimed at

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overcoming regional barriers, improving energy efficiency, and reducing costs, thereby contributing to the global development of the industry [2; 8].

International standards play a key role in ensuring the compatibility of electric vehicle equipment, including charging systems, electric motors, batteries, and communication protocols [2; 6]. The main regulators in the industry are ISO (International Organization for Standardization), IEC (International Electrotechnical Commission), and SAE International, which define technical requirements for power systems, charging infrastructure, batteries, electric drives, and electronic control units. In particular:

– ISO 6469 [16] regulates the safety requirements for high-voltage electric vehicle systems, providing protection against electric shock and thermal risks.

– IEC 61851 [17] and IEC 62196 [13] standardize protocols and connectors for charging stations, promoting global compatibility and energy efficiency.

– SAE J1772 [18] is the basic standard for the North American market, defining the design of charging connectors and power parameters.

– ISO 15118 [14] supports V2G technologies, allowing V2X-enabled electric vehicles (Vehicle-to-Everything – communication between an electric vehicle and the grid, other vehicles, or infrastructure) to integrate with power grids for load balancing.

– ISO/SAE 21434 [19] establishes cybersecurity requirements for V2X-enabled electric vehicles, protecting communication systems, electronic units, and charging infrastructure from cyberattacks.

– IEC 61980-1:2020 [20] defines general requirements for wireless power transfer systems for electric vehicles, regulates the safety, electromagnetic compatibility, and efficiency of wireless charging (SWPT/DWPT), promoting the unification of charging station infrastructure and compatibility with other standards.

– NACS (SAE J3400) [15], promoted by Tesla, is becoming the new standard for charging connectors in the US and is being adopted by other brands.

– GB/T [21], updated in 2023, is key to unification in the Chinese market and has potential for other regions.

– IEC TS 62196 [22] establishes unified safety rules for different types of chargers.

Standards act as a universal “language” of interaction between manufacturers, developers, and users, reducing the risk of technical fragmentation of the market and contributing to the scaling of the electric vehicle industry [8].

The study identified a number of problems with the unification of electrical equipment that complicate the creation of a single global market for electric vehicles.

1. Different supply voltages complicate the unification of batteries and charging systems, as power systems vary from 400 V (Tesla, European models) to 800 V (Porsche, Hyundai) [1].

2. A variety of data exchange protocols hinder interoperability; for example, ISO 15118 [14] and OCPP are used in Europe, while Chinese GB/T [21] standards have their own protocols [2].

3. Incompatibility of charging systems, which increases infrastructure costs, especially in rural areas. CCS, CHAdeMO, and GB/T standards [21] have different connectors and power requirements [6; 7].

4. Differences in electronic unit interfaces complicate diagnostics and repairs, as control systems from different manufacturers (Bosch, Continental) have unique interfaces [9].

5. Regional differences in standards complicate the global use of unified charging systems, for example, the differences between CCS (Europe/USA) and CHAdeMO (Japan) [6].

6. Rapid technological development creates challenges for the harmonization of hardware and software aspects, as fast charging systems (350–500 kW) and intelligent control systems (smart charging, V2G, adaptive battery temperature control) require rapid updating of standards [6].

7. Cybersecurity, because the variety of communication protocols (ISO 15118 [14], OCPP) and the connection of V2X-enabled electric vehicles to networks create vulnerabilities to cyberattacks, such as unauthorized access to ECUs or manipulation of charging systems. For example, weaknesses in OCPP require strengthening TLS and authentication, and UN regulations R155 [23]/R156 [24] require security standards [9].

8. Wireless charging complicates the integration of standards, as communication standards for static (SWPT) and dynamic (DWPT) wireless charging remain fragmented [6].

In Ukraine, limited charging infrastructure and military risks exacerbate these problems, complicating integration with international standards and reducing the market appeal of electric vehicles [4; 10].

The identified problems are evident in real attempts at unification, which illustrate both successes and failures in harmonizing standards.

Successful examples include the NACS (SAE J3400) standard [15] promoted by Tesla, which has reduced infrastructure costs in North America by 15% and simplified access to charging stations [11]. In Europe, CCS2 [13] has become the basis for most new electric vehicles, ensuring compatibility and supporting fast charging up to 350 kW [2]. In Ukraine, import subsidies for components support local standardization, promoting the development of production [4].

On the other hand, unsuccessful attempts demonstrate the barriers of regional fragmentation. Funke, S.Á. et al. [6] note that the CHAdeMO standard is losing ground in Europe and the US due to limited support, forcing Japanese manufacturers (e.g., Nissan) to adapt models such as the Leaf to CCS, which increases the cost by 10–20%. The Chinese GB/T standard [21], which is effective locally but incompatible with CCS or CHAdeMO, limits the export of Chinese electric vehicles [6]. In Ukraine, these problems complicate the development of charging networks due to military risks and limited infrastructure, reducing consumer perception and market appeal [10; 4]. At the same time, the progress of NACS in the US does not solve global fragmentation [7].

To overcome the identified problems, the following is proposed:

1. Universal charging modules, such as the development of modular charging systems compatible with CCS, CHAdeMO, and GB/T [21], will reduce infrastructure costs and increase accessibility in rural areas [7]. The implementation of IEC 61851-21-2 [25] will ensure the electromagnetic compatibility of charging systems, reducing interference with power electronics.

2. Uniform communication protocols, such as the promotion of ISO 15118 [14] as a global standard for V2G and diagnostics for V2X-enabled electric vehicles, will improve energy efficiency and compatibility [3].

3. Modular electrical equipment architectures with the introduction of modular batteries and electric motors adapted to different electric vehicle models [10]. ISO 6469-1 [26] regulates the protection of batteries from mechanical damage, ensuring safety in accidents and vibrations.

4.Local initiatives in Ukraine to adapt standards such as CCS2 [13] to Ukrainian infrastructure, taking into account the balancing of energy systems and import privileges for components [4; 7].

5. Integration of cybersecurity standards with the implementation of ISO/SAE 21434 [19] and UN regulations R155 [23]/R156 [24] to protect V2X-enabled electric vehicles from cyberattacks, especially for V2G [9].

6. Development of intelligent systems with the integration of smart charging, adaptive battery temperature control, and wireless charging via unified protocols [1]. ISO 19363 [27] standardizes wireless charging, promoting its compatibility and safety.

Unification of electrical equipment, including cybersecurity, can reduce the cost of electric vehicle production by 15…20% through component standardization. For consumers, this means more affordable prices and easier access to charging infrastructure, especially in Ukraine. For manufacturers, standardization simplifies supply chains, reduces service costs, and increases competitiveness. The implementation of cybersecurity standards (ISO/SAE 21434 [19], R155 [23]/R156 [24]) will protect electric vehicles from cyber threats, which is important for V2G. In Ukraine, unification will promote local production and support energy systems through V2G.

Conclusions and recommendations

Standardization and unification of electric vehicle electrical equipment are key factors in ensuring their energy efficiency, reducing production costs, and accelerating mass adoption. The study showed that international standards play a crucial role in harmonizing power systems, charging infrastructure, communication protocols, and cybersecurity. However, regional differences in standards, diversity of communication protocols, vulnerability to cyberattacks, and fragmentation of wireless charging create significant barriers to global integration. In Ukraine, these problems are exacerbated by limited charging infrastructure and the need to adapt standards to local conditions.

The practical significance of unification lies in reducing the cost of electric vehicle production by 15…20% through the standardization of components such as batteries, electric motors, and inverters,

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as well as simplifying maintenance and increasing energy efficiency through the optimization of V2G technologies and smart charging. For Ukraine, unification will promote the development of local electric vehicle production, integration with power systems, and economic growth through import privileges for components.

For further research, it is recommended to focus on developing hybrid standards for wireless charging (SWPT/DWPT) and improving cybersecurity for electric vehicles with V2X through the implementation of ISO/SAE 21434 standards and UN R155/R156 regulations.

To harmonize international standards, it is proposed to create universal charging modules compatible with CCS, CHAdeMO, and GB/T, and to promote ISO 15118 as a global protocol. In Ukraine, it is recommended to adapt the CCS2 standard to the local infrastructure, using import privileges for components to stimulate production.

Prospects for the implementation of unified systems in the coming decade include the transition to modular electrical equipment architectures, which will allow the integration of artificial intelligence for adaptive control and V2G for balancing power grids. This could reduce the energy consumption of electric vehicles by 20-30%, contributing to the creation of a sustainable global electric vehicle market. In Ukraine, unification will support the development of the local electric vehicle industry with a focus on energy efficiency, cybersecurity, and integration with power systems.

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