Research on an Energy-Efficient Electric Starting System for an Autonomous Power Plant with a Combined Power Source

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Abstract. The primary objective of this comprehensive study involves the theoretical formulation and scientific substantiation of a robust methodology for developing high-efficiency, energy-saving electric starter systems for transport diesel-generator units. Powered by advanced hybrid energy sources, these systems ensure guaranteed engine ignition under adverse operating conditions while simultaneously achieving a radical reduction in non-productive energy losses. To achieve this, the research established the fundamental theoretical foundations for adaptive starting systems, investigated rational circuit topologies for integrating hybrid storage devices into DC-buses, and implemented verified mathematical models to describe complex transient processes during hybrid activation modes. Furthermore, supercapacitor module parameters were precisely optimized to ensure stable, fail-safe operation during standard driving cycles. The most significant results include the formulation of a universal design methodology and the establishment of quantitative analytical relationships between peak cranking currents, starter acceleration time, and specific fuel consumption relative to stored energy levels. Experimental validation confirmed that the controlled boosting of cranking speeds by up to 20% can effectively reduce fuel consumption by up to 8.5% per starting cycle. Additionally, precision calculations for storage parameters guarantee effective energy recovery performance within international driving cycles. The significance of these findings lies in the creation of a fundamental framework for intelligent electric starter systems. This methodology enables a 50% reduction in required standard battery capacity through strategic supercapacitor integration. Moreover, it significantly increases the overall service life of electrical equipment by damping peak current loads and qualitatively expanding energy-saving capabilities across the variable operating modes of modern transport power systems.

Keywords**:** electric transport, electric vehicle, power plant, automatic control, electrical apparatus, electrical machines, mathematical modelling, electrical systems and networks, energy legislation.

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Cercetarea sistemului energetic eficient de pornire electrică a unei instalații energetice autonome cu sursă combinată de alimentare

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Abstract. Obiectivele principale ale cercetării constau în construirea teoretică și fundamentarea științifică a unei metodologii complexe pentru crearea unui sistem de pornire electrică a motorului diesel al unui generator de transport, care să fie foarte eficient și să economisească energie, care funcționează de la o sursă combinată de alimentare cu energie electrică, necesară pentru a asigura pornirea garantată a motorului în condiții de exploatare complicate și reducerea radicală a pierderilor energetice neproductive. Pentru atingerea obiectivelor stabilite, au fost rezolvate următoarele sarcini: a fost realizată elaborarea detaliată a bazelor teoretice ale metodologiei de construire a sistemelor adaptive de pornire; a fost efectuată o cercetare sistematică a topologiilor raționale și a soluțiilor schematice pentru integrarea dispozitivelor combinate de acumulare în magistrala comună de curent continuu a rețelei de bord; au fost dezvoltate, verificate și implementate din punct de vedere software modele matematice ale proceselor de tranziție la activarea modului de pornire combinată; au fost, de asemenea, definite și optimizate parametrii modulelor supercondensatoare pentru a asigura funcționarea stabilă și fără defecțiuni a instalației în condiții de cicluri de conducere tipice. Cele mai importante rezultate sunt formularea unei metodologii universale pentru construirea de sisteme de pornire eficiente din punct de vedere energetic, precum și stabilirea unor dependențe analitice cantitative între valorile de vârf ale curentului de pornire, timpul de accelerare dinamică a starterului și consumul specific de combustibil în funcție de nivelul de energie stocat în acumulatorul combinat;

s-a obținut confirmarea experimentală a posibilității de reducere a consumului de combustibil cu până la 8.5 % pe un ciclu de pornire prin forțarea controlată a turației de pornire cu până la 20 %; s-a efectuat calculul de precizie al parametrilor acumulatorului, care garantează recuperarea eficientă a energiei în ciclurile internaționale de conducere. Importanța rezultatelor obținute constă în crearea unei metodologii fundamentale de proiectare a sistemelor inteligente de pornire electrică, care permite demonstrarea teoretică și implementarea practică a avantajelor integrării supercondensatoarelor, asigurând o reducere cu 50% a capacității necesare a acumulatorilor standard, o creștere multiplă a resurselor echipamentelor electrice prin amortizarea sarcinilor de curent de vârf și o extindere calitativă a posibilităților de economisire a energiei în regimurile variabile de funcționare ale sistemelor energetice moderne de transport.

***Keywords*:** transport electric, vehicul electric, centrală electrică, control automat, aparatură electrică, mașini electrice, modelare matematică, sisteme și rețele electrice, legislație energetică.

Исследование энергоэффективной системы электрического пуска автономной энергетической установки с комбинированным источником питания

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Аннотация. Основные цели исследования заключаются в теоретическом построении и научном обосновании комплексной методологии создания высокоэффективной и энергосберегающей системы электростартерного пуска транспортной дизель-генераторной установки, функционирующей от комбинированного источника электроснабжения, что необходимо для обеспечения гарантированного запуска двигателя в осложненных эксплуатационных условиях и радикального снижения непроизводительных энергетических потерь. Для достижения поставленных целей были решены следующие задачи: осуществлена детальная разработка теоретических основ методологии построения адаптивных систем пуска; проведено системное исследование рациональных топологий и схемных решений по интеграции комбинированных накопительных устройств в общую шину постоянного тока бортовой сети; разработаны, верифицированы и программно реализованы математические модели переходных процессов при активации режима комбинированного пуска; а также определены и оптимизированы параметры суперконденсаторных модулей для обеспечения стабильной и безотказной работы установки в условиях типовых ездовых циклов. Наиболее важными результатами являются сформулированная универсальная методология построения энергоэффективных систем пуска, а также установление количественных аналитических зависимостей между пиковыми значениями пускового тока, временем динамического ускорения стартера и удельным расходом топлива в зависимости от уровня энергии, запасенной в комбинированном накопителе; получено экспериментальное подтверждение возможности сокращения расхода топлива до 8.5 % на один цикл запуска за счет управляемого форсирования пусковых оборотов до 20 %; выполнен прецизионный расчет параметров накопителя, гарантирующего эффективную рекуперацию энергии в международных ездовых циклах. Значимость полученных результатов состоит в создании фундаментальной методологии проектирования интеллектуальных систем электростартерного пуска, которая позволяет теоретически доказать и практически реализовать преимущества интеграции суперконденсаторов, обеспечивая снижение требуемой емкости штатных аккумуляторов на 50%, кратное увеличение ресурса электрооборудования за счет демпфирования пиковых токовых нагрузок и качественное расширение возможностей энергосбережения в переменных режимах работы современных транспортных энергетических систем.

Ключевые слова: электрический транспорт, автономный транспорт, энергетическая установка, автоматическое управление, электрические аппараты, электрические машины, математическое моделирование, электротехнические системы и сети, энергетическое законодательство.

INTRODUCTION

The relevance of ensuring reliable starter ignition for diesel engines under low-temperature conditions remains a pivotal challenge in the operation of vehicles and specialized machinery across various sectors [1-3]. Global operational experience indicates significant difficulties that lead to obstructed diesel engine starts as ambient temperatures decrease. This issue affects nearly the entire fleet of machinery equipped with conventional electric starter systems [1, 4, 5].

In winter conditions, the reliability of internal combustion engine ignition is compromised by the synergistic effect of two primary factors. First, a substantial increase in motor oil viscosity occurs, resulting in a manifold increase in the torque required for the starter to crank the crankshaft [6, 7]. Second, low temperatures adversely affect the electrochemical processes within traditional lead-acid starter batteries, leading to a critical reduction in their effective capacity and a precipitous drop in maximum discharge current [8, 9].

To enhance the efficiency and reliability of the starting process, the integration of auxiliary electrical energy storage devices operating in conjunction with primary batteries represents a promising research direction [10-12]. The principal advantage of modern energy storage units, specifically supercapacitors (electric double-layer capacitors), lies in their exceptionally high power density, which significantly exceeds that of traditional batteries. This characteristic allows these storage devices to rapidly deliver the high peak currents essential for the starter during the initial cranking phase. Conversely, energy storage units possess lower energy density compared to batteries, and the low nominal voltage of individual cells necessitates complex series or parallel configurations to achieve the required system operating parameters [13-15].

The rational implementation of hybrid power systems, incorporating both batteries and energy storage units, enables the optimization of the ignition process [16]. In this approach, during the initial and most energy-intensive phase, the starter is primarily powered by the energy storage units. This effectively unburdens the battery from peak cranking currents–the primary cause of accelerated wear and degradation–thereby extending the overall service life of the battery units [17-19].

Under conditions of intensive daily operation, particularly with frequent engine starts, the problem of insufficient battery charge recovery emerges. Standard vehicle alternator systems are generally not designed to provide rapid and complete battery recharging during the short intervals between duty cycles [20, 21]. Consequently, a pressing scientific task is the investigation, development, and optimization of energy storage types capable of providing not only rapid energy discharge during starting but also efficient and high-speed recharging from the onboard network between starts. This necessitates the development of optimal connection topologies and control algorithms for hybrid "battery-energy storage" systems, which is a prerequisite for improving the reliability and economic efficiency of diesel machinery, especially in harsh climates. To date, this issue has not been comprehensively addressed.

Therefore, the topic of this article is highly relevant.

The objective of this work is to develop a comprehensive methodology for constructing an energy-efficient electric starter system for a diesel-generator power unit powered by a hybrid electrical source.

To achieve this objective, the following tasks must be addressed:

– the theoretical formulation of a comprehensive methodology for designing an energy-efficient electric starter system for a diesel-generator power unit powered by a hybrid electrical source;

– an analysis of the circuit implementations required to provide a hybrid electrical source for the electric starter system of a diesel-generator unit;

– an analysis of transient processes within the power supply circuit of the diesel-generator electric starter system;

– the selection of energy storage types suitable for various operating conditions of the power unit.

I. RESEARCH METHODS

The problem of complex optimization of energy flows in specialized transport systems, focused on minimizing energy consumption and the cost of generated power, constitutes the scientific and practical basis for designing high-efficiency electric starter systems. The implementation of such systems, functioning within a hybrid power unit based on a diesel generator and a battery bank, requires the formation of multi-level control algorithms. The methodological basis of such control involves the sequential development of a mathematical apparatus to describe the statics and dynamics of both the system as a whole and its key components, the creation of an analytical model to assess the technical and economic efficiency of generation and consumption processes, and the direct software implementation of control actions. Previously developed mathematical models of transient processes in hybrid power source nodes allow for a transition to a comprehensive analysis of energy modes.

The evaluation of cost indicators and the efficiency of energy distribution in transport networks makes it possible to determine the degree of system operational excellence, provided that the starting characteristics of the drive unit are unconditionally guaranteed and regulatory requirements for power quality are met. Such a synergistic approach, combining fundamental laws of electrodynamics and principles of economic theory, is critically important for integrated power systems that supply specific vehicle consumers. Modern requirements for such complexes include not only traditional reliability, safety, and operational maintainability but also increased energy efficiency, necessitated by the need to minimize losses during multiple conversion and energy transfer processes from the diesel-generator set and storage devices to the starter unit.

The structural organization of a transport energy system is traditionally based on a hierarchical principle, covering levels from primary sources and main distribution units to local consumers and terminal buses. Each of these levels is characterized by specific methods for calculating electrical parameters and design tolerances. Applying a differentiated approach to the analysis of active power losses at each hierarchical stage provides an adequate assessment of the system's energy balance. From the perspective of investigating electric starter ignition, it is advisable to segment the overall power system into fragments including power sources (diesel generator and batteries), internal lines, and direct consumer networks. This classification allows for the identification of the most energy-intensive sections and the localization of maximum loss zones during power transmission.

The architecture of a vehicle's power supply system is determined by the nominal voltage, the configuration of auxiliary units, and the required degree of ignition process continuity. The transmission infrastructure, represented by cable lines and busbars, can be implemented using radial or trunk schemes. Radial circuits provide the highest reliability for critical starter system nodes, while trunk and mixed schemes allow for the optimization of the weight, dimensions, and cost characteristics of the onboard network. In the context of hybrid power, the use of hybrid network topologies allows for the most flexible management of energy distribution between the generator set and the batteries.

Systemic analysis of transport power engineering must go beyond standard energy audits, which often view elements in isolation. An effective energy-saving strategy in electric starter systems requires accounting for the inextricable link between energy conversion and consumption processes. An integrated approach implies that the decomposition of the system into functional fragments must strictly correspond to its physical structure and the specific technological operating modes of the diesel engine and electrical storage units. This allows for the consideration of the unique dynamic characteristics of each transport subsystem and the formation of adaptive control algorithms that ensure maximum efficiency of the starting cycle.

The proposed concept of structuring and modeling creates the necessary conditions for the synthesis of control systems capable of real-time optimization of hybrid power source operating modes, minimizing battery degradation and diesel generator fuel consumption while maintaining the required starting dynamics.

The process of energy transfer in a vehicle's electrical lines is inevitably accompanied by active power losses due to fundamental electromagnetic and thermal phenomena in conductive elements and power equipment. Regarding electric starter systems with hybrid power, the existing classification of energy losses is based on the etiology of their occurrence. The primary group of losses includes basic components determined by the nominal operating modes of the hybrid unit components under design parameters, as well as additional losses arising from stochastic deviations of current starting modes from specified specifications.

The second group of destructive factors affecting the energy balance of the "diesel generator – battery – starter" system is classified along the following lines: structural imperfection of the power circuit architecture, reactive power circulation within system elements, irrationality of control algorithms for technological cycles in vehicle nodes, degradation of power quality indicators, and systemic defects in energy distribution organization. In the context of high-efficiency starting, structural imperfection refers to the lack of comprehensive, scientifically grounded approaches to selecting the rated power of units, determining the topological coordinates of power source connection points (batteries and generator), and optimizing the cross-sections of current-carrying lines, which collectively predetermines the integral energy-saving level of the system.

The transportation of reactive power through network elements possessing active resistance provokes not only direct energy losses but also causes several negative effects critical for starting modes. These include a reduction in the throughput capacity of distribution devices and instability in voltage levels, which can adversely affect the starter's cranking torque. The reduction or complete elimination of these flows is achieved through the implementation of reactive power compensation systems, which within a vehicle transforms into a range of engineering tasks: from developing measures to reduce the inherent reactive consumption of actuators to selecting optimal locations and operating modes for compensating devices.

The practical implementation of minimizing reactive component consumption in transport power systems covers a wide range of operational and design measures. Key among these are the optimization of the load factor of power units, the introduction of idle limiters for asynchronous drives of auxiliary systems, and the use of modern semiconductor converters with rational control schemes. Particular attention is paid to the quality of electric motor maintenance and the possibility of using synchronous machines within electric drives where justified by technical and economic analysis. Individual reactive power compensation directly at the high-power consumers of the starting complex significantly unburdens the onboard network and increases the overall energy efficiency of the starter cycle when powered by a hybrid source.

The strategic goal of optimizing and increasing the energy efficiency of electric starter systems with hybrid power is a radical reduction in the level of energy losses during the engine starting cycle. The formation of a list of modernization measures for such complexes should be carried out iteratively and include stages of generating technical solutions, selecting their combinations, and defining a target function while observing the boundary conditions dictated by the operating modes of the diesel-generator set and batteries. The combination of circuit design solutions that minimize losses during power transfer to the starter forms the basis for implementing a dynamically transformable energy infrastructure. This approach allows for the adaptation of system parameters to varying vehicle operating conditions, ensuring flexible energy flow management between sources and consumers.

A key factor in implementing dynamic changes to the power system structure is their mutual correlation. Complete replacement of electrical equipment during the modernization of a starting complex is often economically unjustified despite potential loss reductions, due to the high cost of power network components. Consequently, the task of finding compromise solutions that provide the closest possible approximation to the theoretical minimum of energy expenditure while maintaining economic feasibility becomes relevant. Despite the standardization of design solutions for certain classes of transport, the operational modes of each specific unit are unique, requiring an individual approach to ranking measures based on the criterion of specific cost savings.

To quantitatively evaluate the effectiveness of implemented innovations in hybrid power systems, it is advisable to use technical and economic analysis. Specifically, the economic effect can be expressed through a function that accounts for annual profit from reduced energy losses, renovation depreciation rates, and the standard investment efficiency coefficient. From an investor's perspective, priority is given to scenarios with the maximum net present value (NPV), allowing for the assessment of long-term benefits considering the time value of money and the risks inherent in the operation of autonomous transport power systems.

The methodology for implementing an energy-saving program involves forming a permissible set of technical measures, conducting a comparative analysis of their parameters against current system indicators, and subsequent ranking in descending order of the cost of the saved resource. In this process, current operational costs in transport networks–including generation, maintenance, and repair expenses–are compared with capital investments. The project's payback period and its reciprocal efficiency coefficient become the decisive criteria when choosing between various onboard network topologies or types of energy storage.

Special attention should be paid to the energy-saving potential, defined as the difference between actual losses in the existing configuration and projected losses in the proposed system model. Unlike standard techniques, this approach allows for the explicit identification of the maximum possible technical reserve of the electric starter system. The implementation of these measures must be based on the calculation of specific fuel savings and battery life extension values resulting from the optimization of power transmission parameters. The final efficiency of the program is achieved only through the synergy of the technical validity of design changes and their ability to minimize total active energy losses in the elements of the hybrid power source.

The mathematical description of electromechanical and electromagnetic processes in electric starter systems with hybrid power requires the creation of an adequate analytical analogue that accounts for the specific modes of the diesel generator and batteries. For systemic management of the energy loss level in a vehicle's onboard network, the development of a predictive model is proposed, the key output parameter of which is the total effective energy loss at the stages of generation, distribution, and direct consumption by the starter unit per starting cycle.

The structural synthesis of the model and the functional dependencies between power and network parameters are determined by the permissible approximation error, which, in turn, correlates with the accuracy class of the measurement complexes recording power consumption profiles. An important applied task of modeling is predicting loss dynamics during variations in the topology and parameters of the power circuit over the long term, which is necessary for conducting verified technical and economic analysis.

The choice of method for calculating effective energy losses is based on stable data regarding the equivalent circuit parameters of elements, particularly active resistances. Depending on the completeness of initial information regarding starting loads, deterministic, probabilistic, or statistical approaches may be applied. Under conditions of certainty regarding onboard network parameters and starter characteristics, the deterministic method is prioritized. According to this approach, integral active energy losses in the electric starter system are defined as the product of power losses in the maximum starting current mode and the duration of the peak load interval.

The application of decomposition and hierarchical description principles allows for the division of the starting system into functional levels: generator set buses, main and local distribution devices, connecting lines, and the starter motors themselves. Total energy losses in such a multilevel structure are determined as the sum of losses occurring at each of these hierarchical stages.

For a detailed energy efficiency analysis of specific nodes–for example, when a group of consumers is powered by a specific source–total losses are calculated by summing the losses in all elementary sections of the network. The current load at system nodes depends directly on the ratio of apparent power to nominal voltage. In turn, the specific resistance of each section is determined by the physical properties of the material, the cross-sectional area of the conductor, and the number of parallel lines in the cable route.

The geometric parameters of the network are calculated based on the coordinates of sources and distribution nodes using the shortest distance principle or considering actual cable routing paths. In doing so, several technical constraints are imposed: regarding the number and maximum power of the units used, their load factor, as well as spatial limits that exclude equipment placement in prohibited vehicle zones.

Special attention is paid to topological optimization, accounting for "forbidden zones" for equipment installation. To describe such areas, a method of dividing the plane into regions is used, where inadmissible zones are defined by logical functions. If the calculated coordinates of a network element fall within such a region, it is interpreted by the system as a violation of layout constraints. This approach allows for the automation of the design of energy-efficient electric starter schemes, minimizing losses by selecting optimal power transmission paths while strictly adhering to structural requirements.

This stage of forming the theoretical basis allows for the transition to the direct algorithmization of control processes in hybrid starting systems.

The connection of the storage device to the common DC bus is assumed based on the circuit shown in Fig. 1 [22].

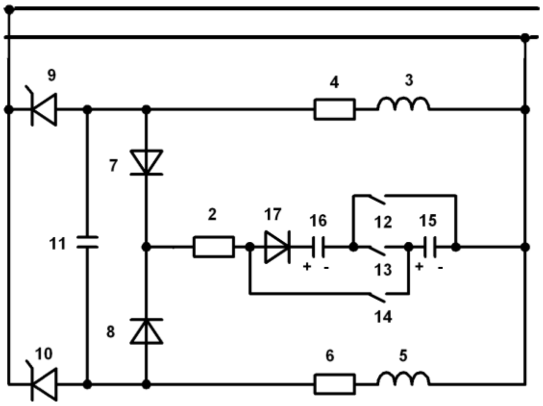

Fig. 1. Schematic diagram of the storage device connection to the common DC bus of the diesel-generator power unit.

This circuit operates as follows. To enhance the efficiency of the capacitive charge, a converter (charging device) based on the electromagnetic inductor principle is utilized. In this configuration, energy from the common DC bus (1) is alternately stored in inductors (3) and (5), and subsequently accumulated in capacitors (15) and (16) via diodes (7) and (8). The inductor is charged until a predefined maximum current value is reached, at which point the circuit is interrupted by thyristor (9) or (10), forcing the current to flow through the capacitance. The switching frequency of the thyristors is determined by the control unit. The capacitance itself is divided into two equal sections to facilitate voltage regulation during the charging process. The discharge time of the inductance within the closed L-C circuit depends on the capacitance value C and its corresponding voltage. As the voltage increases and the capacitance decreases, the discharge rate of the inductor accelerates.

Consider the following equivalent circuit of the starter network, which includes battery E, while the starter is represented by the inductance and active resistance of its armature, along with the resistance of the starter network (Fig. 2).

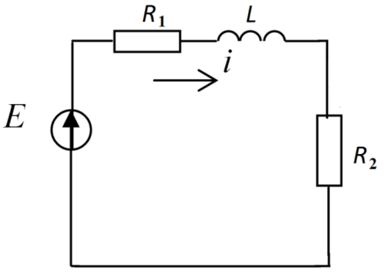

Fig. 2. Equivalent circuit of the starter network.

To investigate the hybrid starter ignition mode, a capacitor storage unit is integrated into the circuit (Fig. 3). In this case, it is assumed that the capacitance is fully charged, and its connection is initiated automatically by the automatic control system at the moment of starter activation.

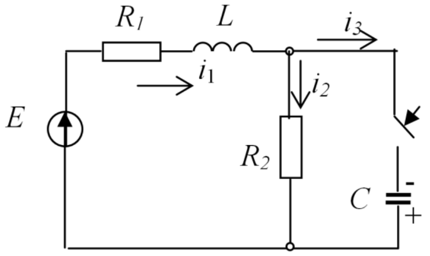

Fig. 3. Equivalent circuit of the starter network with a storage capacitor.

Since the voltage across the capacitor is the sum of the steady-state and transient voltage components, it follows that:

$$u_C = u_{C1} + u_{C2}. \tag{1}$$

The equivalent circuit for determining the steady-state voltage component is presented in Fig. 4.

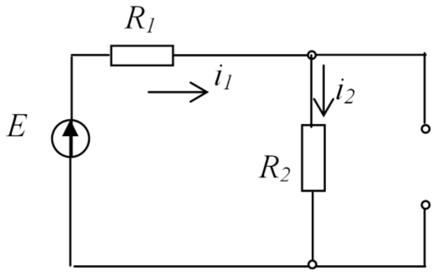

Fig. 4. Calculation circuit for determining the steady-state voltage component.

After commutation $i_3 = 0$, $i_1 = i_2$.

$$u_{C1} = \frac{E}{R_1 + R_2} \cdot R_2. \tag{2}$$

The calculation circuit is shown in Fig. 5. We shall define $Z(p)$.

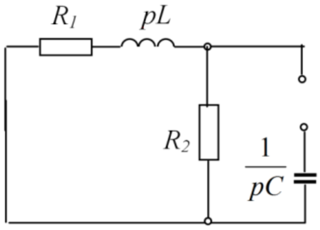

Fig. 5. Calculation circuit for determining the characteristic input impedance from the switch side.

$$Z(p) = \frac{1}{pC} + \frac{(R_1 + pL)R_2}{R_1 + R_2 + pL} =$$
$$= \frac{R_1 + R_2 + pL + pCR_1R_2 + p^2CLR_2}{pC(R_1 + R_2 + pL)} = 0 \tag{3}$$
$$p^2CLR_2 + p(L + CR_1R_2) + (R_1 + R_2) = 0.$$

Then,

$$u_{C2}(t) = A_1e^{pt} + A_2te^{pt}. \tag{4}$$

The values of A_1 and A_2 are found from the initial conditions:

$$\begin{cases} u_C = u_{C1} + A_1e^{pt} + A_2te^{pt}; \\ \dfrac{du_C}{dt} = pA_1e^{pt} + pA_2te^{pt} + A_2e^{pt}. \end{cases} \tag{5}$$

If $t = 0$

$$\begin{cases} u_C(0) = u_y + A_1; \\ \dfrac{du_C}{dt}\Big|_{t=0} = pA_1 + A_2, \end{cases} \tag{6}$$

where $u_C(0)$ – voltage at the moment of switching.

For the given circuit, the following can be written:

$$\frac{du_C}{dt}\Big|_{t=0} = \frac{i_3(0)}{C}. \tag{7}$$

The magnitude of the current $i_1(0)$

$$i_1(0) = i_1(0^-) = \frac{E}{R_1 + R_2}. \qquad (8)$$

The current in the second branch at the initial moment of time is equal to $i_2(0) = \frac{u_C(0)}{R_2}$.

Then $i_3(0) = i_1(0) - i_2(0)$.

The current of the third branch

$$i_3 = C\frac{du_C}{dt} = C\left(pA_1e^{pt} + pA_2te^{pt} + A_2e^{pt}\right). \qquad (9)$$

The current in the second branch is given by

$$i_2 = \frac{u_C(t)}{R_2}. \qquad (10)$$

The current in the first branch

$$i_1 = i_2 + i_3. \qquad (11)$$

Based on the derived expressions and the proposed methodology for evaluating the impact of the suggested measures on diesel fuel consumption, an assessment of the influence of employing a starter-based ignition system was conducted, utilizing performance data from the Caterpillar 3516 power plant [23-25]. Specifically, the implementation of the proposed starter system, integrated with a battery and a capacitive energy storage unit, enables a reduction in diesel engine startup time by accelerating the ignition process through the storage system. According to the manufacturer's technical specifications, the specific fuel consumption during startup is 350 g/kW·h. The resulting fuel consumption metrics are summarized in Table 1.

Furthermore, it should be noted that increasing the starting speed by more than 20% is considered unacceptable. Consequently, it is possible to achieve a maximum reduction in fuel consumption of up to 8.5% per single start.

An analysis was conducted on the installation of storage devices that accumulate electrical energy directly, without conversion into other forms for storage. This constraint is necessitated by the requirement for extensive research to analyze the efficiency of storage systems involving the preliminary conversion of electrical energy into other forms (such as hydrogen, flywheel, pneumatic, hydraulic, and others), which falls outside the scope of the present study.

Table 1.
Comparative characteristics of diesel engine startup.

Variation in starter shaft rotational speed resulting from energy supplied by the storage system	Specific fuel consumption during startup, g/kW·h	Relative change indicator of specific fuel consumption during startup
1	350	1
1.1	336.35	0.961
1.15	330.05	0.943
1.2	320.25	0.915

A comparative analysis was performed on the two primary types of electrical energy storage systems: electrochemical batteries and capacitive storage devices. Their fundamental technical specifications are presented in Table 2.

Table 2.
Comparative characteristics of energy storage systems.

Comparative parameter	Lead-Acid Battery	Alkaline Battery	Lithium-Ion Battery	Electrochemical Capacitor
Specific energy, W·h/kg	25-45	15-90	6-245	2-25
Volumetric density, MW·h/m³	190	175	140	5
Maximum specific power, W/kg	250	1350	3500	12600
Cycle life, cycles	1500	2000	1500	$> 10^6$
Cycle duration, s	> 180	> 100	> 80	$> 10^{-6}$
Service life, years	3-10	3-15	5-10	20-50
Operating temperature, ^{0}C	–30/+45	–40/+60	–30/+60	–50/+70
Cycle efficiency, %	85	80	90	98
Maintenance requirements	+	+	+	–

Average cost per kW·h, units of account	50	100	1800	2000
Average cost per kW, units of account	90	350	540	70

Based on the data from the last table, it is concluded that a capacitive energy storage system based on electrochemical capacitor modules, or supercapacitors, should be used as the energy storage device. As an alternative to supercapacitors, battery packs (NiMH or Li-Ion) can be used, which possess significantly higher specific energy.

However, their use is associated with restrictions on charging and discharging modes, and most importantly, they are at least twice as inferior to supercapacitors in terms of cycle life [26]. This means that during the period of operation, the consumer will have to replace a powerful battery at least several times. At the same time, supercapacitors do not require replacement throughout the entire service life, which correlates with the service life of the vehicle [27].

An assessment of the required capacity of the storage system will be performed. It is assumed that the purpose of the energy storage device is to ensure the operation of the diesel generator set in a constant mode, that is, with a constant average operating power. This means that when a need arises for a portion of power to provide for auxiliary needs that exceeds the power generated by the generator, such energy is taken from the storage link.

The storage device can be charged in advance (before the trip), during movement (if the power required for traction is less than that generated by the generator, or during parking with the engine running, movement in idle mode, or movement with partial load), as well as during braking–from the traction electric motors.

For a given operating mode of a certain duration, for which the dependence of power consumption on time is known, with a corresponding value of the generator power planned for installation to operate at a constant power, it is necessary to determine the initial charge of the onboard storage system at the time the storage device begins to discharge, sufficient to implement the given operating mode.

At the same time, it will be taken into account that some typical operating modes of the vehicle require the sequential implementation of several similar but not identical cycles of alternating traction and braking.

An assessment of the storage capacity will be performed for schemes of continuous and intermittent operating modes of the power plant.

To calculate the capacity, formula [28] will be used

$$C=\frac{G_a\left(\frac{\upsilon_1^2-\upsilon_2^2}{g}+t\cdot\sin\alpha\cdot\left(\upsilon_1+\upsilon_2\right)\right)}{\left(U_{\max}^2-U_{\min}^2\right)\eta},\qquad(12)$$

where G_a – vehicle weight;

η – cycle conversion efficiency;

$U_{\max},U_{\min}$ – respectively, the maximum and minimum voltage corresponding to the operating cycle of the storage element;

υ_1,υ_2 – maximum and minimum movement speeds when the storage system is connected;

t – operating time of the power plant;

α – track gradient.

As shown in [29], the main parameter of the controlled electric drive circuit is the ratio of the resistive short-circuit power at the load terminals to the useful active load power:

$$k_{SC}=\frac{P_{SC}}{P_{usf}}\qquad(13)$$

where P_{usf} – average active load power over a time interval equal to the repeatability period *T*, calculated as a period of time containing an integer *q* of source voltage repeatability periods and a number *r* of repeatability periods of the instantaneous active load power graph; the numbers *q* and *r* are coprime.

In the case of the random nature of processes, the total repeatability period is determined approximately, taking into account the dependence of efficiency on the variable component of the instantaneous active power graph [30]. Resistive short-circuit power P_{SC} is determined according to the methodology shown in [31]. To account for the portion of energy returned to the source, the energy recovery coefficient (energy return to source coefficient) is introduced (14).

$$0 \le k_E = \frac{P_{S\leftarrow}}{P_{S\rightarrow}} \le 1, \qquad (14)$$

where $P_{S\leftarrow}$ – source power in the forward direction;

$P_{S\rightarrow}$ – source power in the reverse direction.

$$\eta_{\max\rightarrow} = 0.5 + \sqrt{0.25 - \frac{1}{k_{SC}}}. \qquad (15)$$

Then the maximum possible efficiency of the traction system in a bidirectional flow can be determined by considering the portion of energy consumed from the grid, taking into account the portion of energy returned to the source and the losses in both unidirectional flows ($\Delta P_{\min\rightarrow}, \Delta P_{\min\leftarrow}$):

$$\eta_{\max\leftrightarrow} = \frac{P_{S\rightarrow} - P_{S\leftarrow} - \Delta P_{\min\rightarrow} - \Delta P_{\min\leftarrow}}{P_{S\rightarrow} - P_{S\leftarrow}}. \qquad (16)$$

It is obvious that for regenerative braking on steep gradients during descent

$$P_{S\leftarrow} = P_{pot} - \Delta P_{\min\rightarrow} - \Delta P_{\min\leftarrow}, \qquad (17)$$

When braking to a complete stop

$$P_{S\leftarrow} = P_{pot} + P_{kin} - \Delta P_{\min\rightarrow} - \Delta P_{\min\leftarrow}, \qquad (18)$$

Maximum possible efficiency of the traction system in a bidirectional flow for regenerative braking on steep gradients during descent:

$$\eta_{\max\leftrightarrow} = \frac{P_{S\rightarrow} - P_{pot}}{P_{S\rightarrow} - P_{pot} + \Delta P_{\min\rightarrow} + \Delta P_{\min\leftarrow}}, \qquad (19)$$

and when braking to a complete stop:

$$\eta_{\max\leftrightarrow} = \frac{P_{S\rightarrow} - P_{pot} - P_{kin}}{P_{S\rightarrow} - P_{pot} - P_{kin} + \Delta P_{\min\rightarrow} + \Delta P_{\min\leftarrow}}, \qquad (20)$$

To evaluate the influence of the initial braking speed and the gradient magnitude, we shall write the following expressions for the maximum possible efficiency of the traction system in a bidirectional flow for regenerative braking on steep gradients during descent and when braking to a complete stop:

$$\eta_{\max\leftrightarrow} = \frac{P_{S\rightarrow} t - mgli}{P_{S\rightarrow} t - mgli + \Delta P_{\min\rightarrow} t + \Delta P_{\min\leftarrow} t}, \qquad (21)$$

where t – travel time on the gradient;

m – vehicle mass;

l – horizontal track profile length;

i – track gradient relative to the horizontal plane.

When braking to a complete stop:

$$\eta_{\max\leftrightarrow} = \frac{2\left(P_{S\rightarrow} t - mgli\right) - m\upsilon^2}{2\left(P_{S\rightarrow} t - mgli + \Delta P_{\min\rightarrow} t + \Delta P_{\min\leftarrow} t\right) - m\upsilon^2}, \qquad (22)$$

where υ – initial braking speed.

The modern architecture of European legislation in the field of electric vehicle energy efficiency is based on a transition from local emission reduction to the concept of systemic integration of the vehicle into the power grid. A key regulatory instrument is the updated "Fit for 55" package and Regulation 2023/851, establishes stricter CO_2 emission standards for new fleets, incentivizing manufacturers to implement high-efficiency powertrains. Simultaneously, the Alternative Fuels Infrastructure Regulation and the Renewable Energy Directive mandate intelligent charging systems and Vehicle-to-Grid technologies, allowing electric vehicles to be used as mobile storage units for balancing the energy system. Particular attention is paid to the full product lifecycle through the new Battery Regulation, which introduces digital passports and strict requirements for the production carbon footprint. Thus, the European legal framework forms a holistic ecosystem where energy efficiency is defined not only by low kW·h per kilometer consumption but also by the minimization of energy expenditures at all stages – from raw material extraction to the recycling of components.

II. RESULTS AND DISCUSSION

As an example, we will assess the energy storage capacity for various operating modes of the power plant for a "Belarus 3023" type tractor. We will consider a curb-weight tractor based on the specifications of a tractor with a trailer (where the trailer weight provides the nominal drawbar load) traveling on an asphalt highway. The maximum gradient values are assumed to be 4 degrees, which corresponds to the average value for the terrain of Ukraine.

For the storage unit, we will consider a ultracapacitor with a nominal voltage of 650 V, with a maximum voltage fluctuation during the duty cycle down to 331.5 V. The nominal capacitance of one such capacitor, model EKHNE-96-9, is 9 F.

To analyze the level of accumulated energy, we will conduct a study of the tractor in accordance with the standard New European Driving Cycle (NEDC) (Fig. 6).

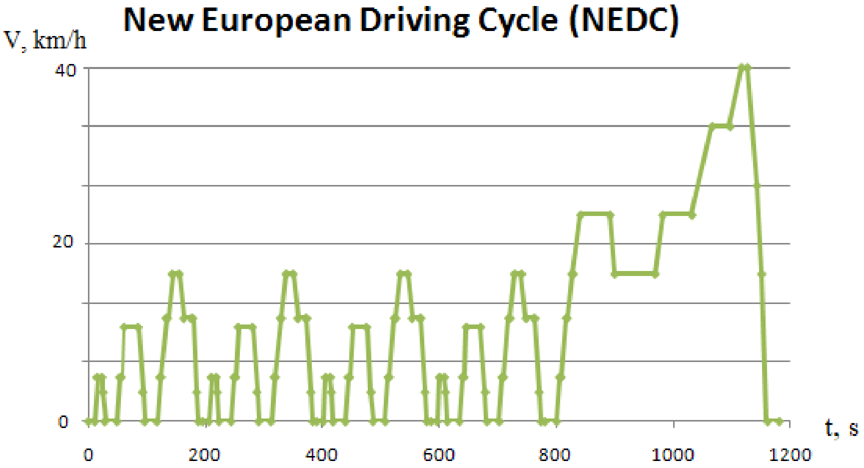

Fig. 6. NEDC standard driving cycle diagram

For comparison, we will also consider the standard ECE 15 driving cycle (Fig. 7), the EUDC driving cycle (Fig. 8), and the FTP-75 driving cycle (Fig. 9).

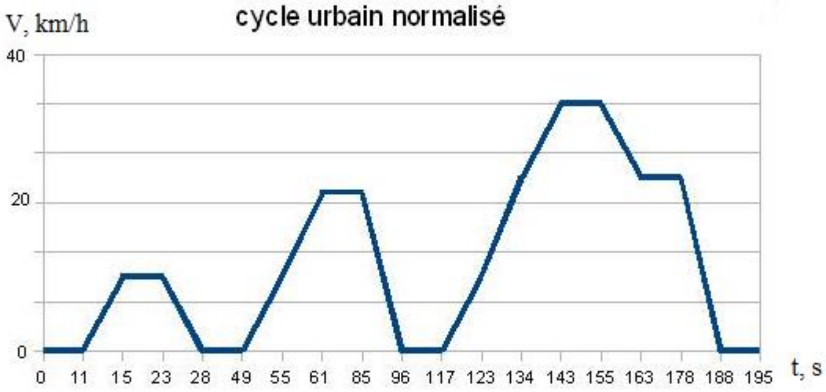

Fig. 7. ECE 15 standard driving cycle diagram

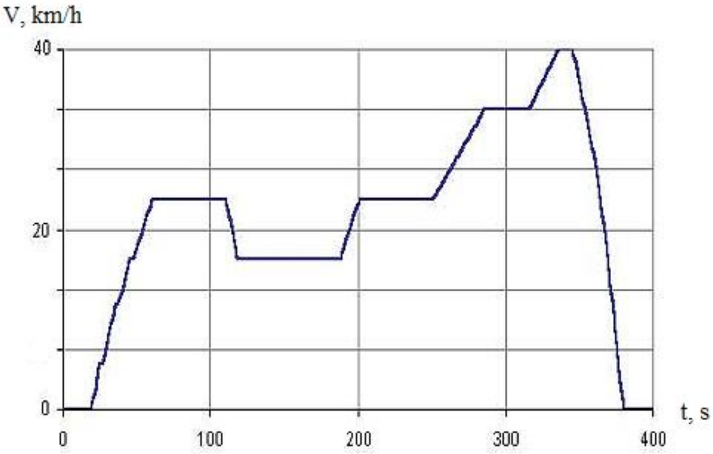

Fig. 8. EUDC standard driving cycle diagram.

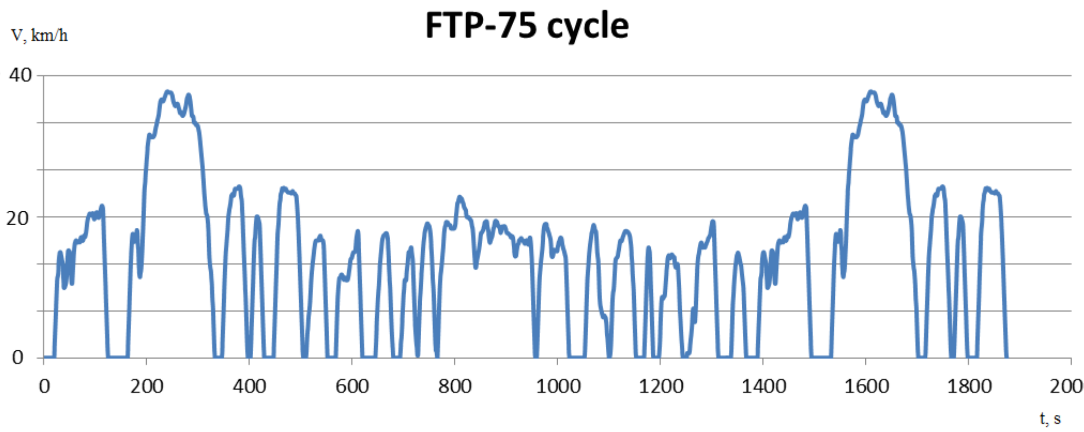

Fig. 9. FTP-75 standard driving cycle diagram.

The calculation results are summarized in Table 3. The calculation of the energy expended on movement per cycle, the amount of recuperated energy, and the energy savings due to regeneration will be performed according to the standard methodology provided in [28].

Table 3.

Comparative characteristics of test driving cycles.

Comparative indicator	NEDC Cycle	ECE 15 Cycle	EUDC Cycle	FTP-75 Cycle
Energy expended on movement per cycle, kW·h	1563.5	213.58	921.15	2615.32
Energy recuperated per cycle, kW·h	209.66	24.177	93.31	407.46
Percentage of energy savings due to energy accumulated during the cycle	13.41	11.32	10.13	15.58

Based on the data provided, a storage system with a capacity of 15.8 F will be sufficient. The mass of such a capacitor unit would be 87 kg, enabling the tractor to move fully autonomously for a distance of 1.132 km. Using this same storage unit for starter engagement allows for a 47% reduction in the nominal capacity of the storage battery compared to a standard battery (215 Ah capacity), provided the battery is fully discharged. Below is a diagram showing the amount of accumulated energy depending on the initial and final braking speeds according to the FTP-75 cycle (Fig. 10).

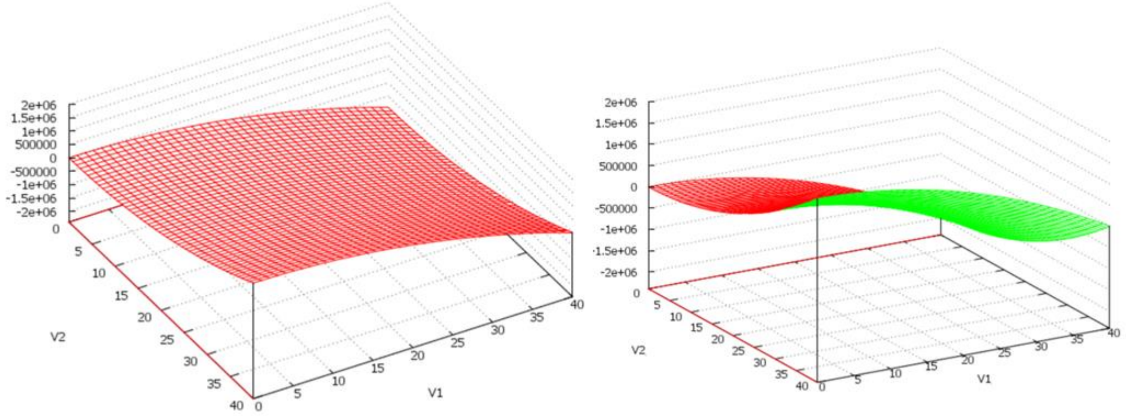

Fig. 10. Energy accumulation diagram as a function of initial and final braking speeds according to the FTP-75 cycle.

III. CONCLUSIONS

Fundamental principles for designing high-efficiency electric starter transport systems with combined power supply have been formulated. It is established that the basis for constructing such systems is the minimization of energy costs and the cost of generated power in onboard networks. Implementing this task requires the development of multi-level control algorithms based on sequential modeling of static and dynamic processes both in the system as a whole and in its individual components, including the diesel-generator set and the battery unit. Within the framework of the study, the expediency of decomposing the energy system into functional fragments is justified, allowing for a detailed breakdown of the loss structure in each vehicle compartment and the development of targeted energy-saving measures without disturbing the integrity of the energy balance.

Key factors for energy losses in integrated AC transport networks have been identified. The process of power transmission to starting devices is inevitably accompanied by active energy losses due to thermal and electromagnetic phenomena in conductors and power equipment. Particular attention is paid to the destructive influence of reactive power, the circulation of which through active network resistances triggers voltage drops and reduces the throughput capacity of distribution channels. It is proven that the elimination of these effects is achievable through integrated reactive power compensation, including optimization of onboard consumer operating modes, selection of rational connection points for compensating devices, and the use of modern control algorithms for power conversion equipment.

A system of evaluation criteria and a methodology for improving the energy efficiency of starting complexes have been developed. The process of selecting optimal modernization solutions is presented as a sequence of stages: from forming an excessive set of technical measures to selecting the most effective combinations based on a specified objective function. The formed array of solutions, limited by operational and technological frameworks, allows for the minimization of losses in the engine starting cycle. Practical aspects such as increasing the load factor of units, implementing idle-limiting systems, and the possibility of replacing asynchronous drives of auxiliary systems with synchronous analogs are considered, which collectively increases the overall efficiency of the energy system.

A hierarchical model of the transport energy system based on the decomposition principle is proposed. The system is presented as a structured set of levels, including generation buses, main switchgears, local networks, and terminal starting elements. This approach allows for block-by-block design and optimization of each node to achieve a global minimum of energy losses. For the first time, a formulated generalized concept for building energy-efficient starting systems based on diesel generators and energy storage units creates a scientific basis for unifying parameter calculation methods and improving the operational characteristics of modern vehicles. The practical significance of the results lies in the ability to accurately localize and systematize losses, opening paths to a significant reduction in the energy intensity of starter modes and extending the resource of onboard network equipment.

A comprehensive analysis of the electric starter system for a transport diesel-generator power plant fed by a combined power source was conducted, aiming to increase starting reliability in various operating conditions and reduce the energy losses of traditional battery systems. The study justified the effectiveness of integrating supercapacitor storage units into combined power supply systems, which significantly increases starting reliability and efficiency.

Thanks to the application of the proposed starter system using a battery and a capacitive storage unit, it is possible to reduce diesel engine starting time by boosting the starting process from the storage system. It was established that a maximum fuel consumption saving of up to 8.5% per start can be achieved by increasing the starter's cranking speed by up to 20%.

A comparative analysis of electric energy storage units showed that supercapacitors (electrochemical capacitors) are the most preferred for use in combined systems due to their exceptionally high power density, a resource of more than 10^6 cycles, and a significant service life (20-50 years). This eliminates the need for their replacement throughout the entire service life of the vehicle, unlike storage batteries. It was calculated that using a capacitive storage unit for starter engagement allows for a reduction in the nominal capacity of the storage battery by almost 50% compared to a standard battery, while also expanding the possibilities for energy recovery in variable transport system operating modes.

In summary, the new generation of European legislation has definitively established the role of electric transport as a fundamental element of decarbonization, transforming it from an autonomous means of transportation into an active resource for the energy system. Through the synergy of standards and the updated Battery Regulation, the priority has shifted from the energy efficiency of an individual motor to the optimization of the vehicle's entire lifecycle. The implementation of mandatory intelligent charging systems and strict control over the production carbon footprint demonstrate the EU's transition to a circular economy strategy, where the technological excellence of electric vehicles directly translates into the stability and energy independence of the entire community.

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