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ENERGY-SHAPPING CASCADE CONTROL OF A TRACTION ELECTRIC DRIVE SYSTEM WITH A HYBRID POWER SOURCE

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The article presents the structure and operating principles of an electric drive system for a vehicle with a hybrid energy storage system that combines a fuel cell and a supercapacitor connected via controlled DC-DC converters with a common DC bus. The traction drive functions are performed by a brushless DC motor (BLDC) powered by three-phase voltage from an inverter connected to the DC bus. The fuel cell is the main source of energy, ensuring stable operation of the system in nominal modes, while the supercapacitor compensates for peak loads, improves dynamics and increases recovery efficiency.

The work justifies the choice of the architecture of a hybrid fuel cell-supercapacitor energy storage system and analyses energy flows and interactions between components through controlled DC-DC converters. Particular attention is paid to the implementation of the energy-forming control principle in a cascade with a PI speed controller, which ensures the coordination of energy sources, extends the fuel cell's service life, and performs drive tasks. The proposed approach is aimed at improving system controllability and drive stability during transient processes.

The research results confirm the feasibility of using a combined 'fuel cell – supercapacitor' architecture in transport electric drives with energy-shaping control. Such a system ensures high efficiency, voltage stability in the common DC bus, rapid response to load changes, and expands the possibilities for energy recovery during braking.

Keywords: vehicle, fuel cell, supercapacitor, hybrid energy storage system, brushless DC motor, cascade control, energy-shaping control.

Introduction

Increasing demands for energy efficiency, autonomy and speed of electric vehicle and transport drives are driving the widespread use of hybrid energy storage systems (HESS), which combine sources with high energy density (lithium-ion batteries, fuel cells) and sources with high specific power and fast response (supercapacitors) [1,2]. This combined architecture enables the smooth distribution of peak loads, extends the service life of components such as batteries, and ensures efficient energy regeneration during braking.

The relevance of researching energy-shaping control systems for electric transport drives with HESS is determined by global trends in the development of electric transport and increasing requirements for energy efficiency, environmental safety, and reliability of transport systems. In the context of the global transition to low-carbon technologies, the transport industry is undergoing the most significant changes: the share of electric vehicles, hybrid vehicles, and autonomous platforms with electric drives is increasing. According to the IEA, the number of electric vehicles worldwide exceeded 40 million in 2024, and the forecast for 2030 is more than 200 million units, which requires improvements to the architecture of power supply and energy flow management systems [3].

Traditional electric drive control schemes often overlook the complex interaction between different types of energy sources, including fuel cells (FC), batteries, and supercapacitors (SC), and fail to provide optimal power distribution during dynamic driving modes [4]. This results in excessive energy losses, uneven loading of energy storage elements, and reduced system durability. That is why it is important to move from traditional current and voltage control schemes to energy-oriented or energy-shaping control concepts, which focus on the formation and balancing of energy flows throughout the entire complex [5,6].

Additionally, electric transport drives with hybrid energy storage systems are considered an effective solution for reducing weight and increasing the energy density of on-board power sources. The combination of a fuel cell, a battery, and a supercapacitor allows for the distribution of functions between the elements: the fuel cell operates in a steady state with maximum efficiency, the battery provides average hourly loads, and the supercapacitor covers peak power during acceleration or braking. This approach not only increases energy efficiency but also enables a reduction in battery size and extension of its service life by reducing cyclic loads [7].

At the same time, integrating heterogeneous energy sources into a single control system is a challenging task due to the different dynamics, non-linearity, and interdependence of the subsystems. In particular, the fuel cell has limited speed due to the inertial processes of the chemical reaction, while the supercapacitor reacts instantly but has limited capacity. Ensuring a stable power supply to the drive motor under such conditions requires the implementation of intelligent control strategies that take into account the instantaneous state of each system element and ensure coordinated energy functioning [8,9].

Energy-shaping control meets these requirements because it is based on the principles of energy modelling, passivity and energy flow conservation. It allows not only to stabilise the operation of the electric drive, but also to actively control the energy balance of the system, taking into account external disturbances, changes in driving modes and degradation of storage elements. This is especially important for modern vehicles operating in modes with high load variability, such as city traffic, frequent stops, and brake energy recovery [10].

Thus, the relevance of the research topic lies in the need to create scientifically based methods for synthesising energy-shaping control systems for electric drives with hybrid energy sources. The development of such systems ensures increased energy efficiency, reliability, and environmental friendliness of electric transport, which aligns with the strategic goals of sustainable development of energy and transport infrastructure.

Analysis of previous studies and publications

Contemporary literature clearly consolidates knowledge that combined fuel cell + supercapacitor schemes produce a synergistic effect: fuel cells provide high energy reserves and long-term autonomy, while the supercapacitor provides instantaneous peak currents and efficient recuperation [11]. Reviews of state of art systematise the characteristics of components (energy and power density, cyclability, response dynamics) and show that the right architecture and energy management strategy (EMS) significantly increase the efficiency and utilisation of supercapacitors [11,12]. The analysis shows that the primary technical challenges are the optimal size of components, the trade-off between the number of converters (complexity vs. losses) and the integration of degradation models into control strategies [13].

The connection topologies of energy storage devices and their power electronics have a significant impact on the energy efficiency of the system. Recent work compares two practically important strategies: architectures with separate DC–DC converters for each storage device (maximum control flexibility, but higher weight and losses) and integrated topologies with fewer converters (lower losses and simpler hardware implementation) [14]. The importance of considering real losses in power switches, inductances, and heat dissipation processes in the optimal design of HESS for transportation applications is emphasised in [15].

Classic rule-based EMS remain popular due to their simplicity of implementation and real-time reliability, but often do not provide global optimality. Model predictive control (MPC) methods enable the consideration of system constraints, load forecasts, and component degradation [16], although they require significant computational resources. Some works demonstrate hybrid schemes where MPC is combined with local rule-based layers to reduce computational requirements [17]. Machine learning-based approaches (in particular, deep-RL) show potential for adaptive energy management, but require a large training sample and formal guarantees of safe operation [18].

In recent years, there has been growing interest in energy-oriented methods of drive system control, in particular energy-shaping and passivity-based control (PBC). These approaches are naturally compatible with HESS, as they work with the energy functions of the system, are easily integrated with source and storage models, and provide formal guarantees of stability [19]. Practical results demonstrate that the use of PBC in combination with DC–DC converters enables the stabilisation of the bus voltage and reduces the risk of overregulation [20].

Comparative analyses of electric motors for traction systems show that brushless DC (BLDC) motors remain a preferred choice for small and medium-sized transport platforms due to their high efficiency, simple cooling system, compactness, and absence of brushes [21]. Its use is particularly appropriate in systems that provide active energy recovery and energy-oriented control, which requires a simple model of electromechanical interaction.

Experimental studies from 2023 to 2025 demonstrate a gradual transition from simulations to physical HESS mock-ups that integrate predictive and energy-oriented control methods. Particular attention is paid to hierarchical EMS, in which local high-speed circuits control SC, and a global optimiser coordinates the operation of FC and batteries [22]. There is also growing interest in economic life cycle models (LCC) and topology optimisation, taking into account losses and thermal effects.

Problem statement

The aim of the work is to develop a cascaded control system for a traction electric drive with a hybrid energy storage system based on BLDC, which ensures coordination of energy processes between the fuel cell and the supercapacitor and optimises their joint operation.

The tasks to be solved by the work are:

- review and analysis of modern HESS architectures and selection of an architecture for an electric vehicle drive system;
- analysis of the possibilities of applying energy-oriented drive control methods, in particular PBC and energy shaping;
- development of an energy-shaping control system that combines PBC at the lower level and EMS at the upper level;

Presentation of the main material

Hybrid energy storage systems combine different types of storage devices to achieve a balance between high energy density and power. The most common combinations are those in which one element provides a long-term energy supply and the other responds quickly to dynamic loads.

A typical structure is a battery-supercapacitor system, in which the battery (usually lithium-ion) covers the main energy demand, and the supercapacitor takes short-term peak loads during acceleration or recuperation. This combination reduces current peaks, increases efficiency and extends battery life, which is why it is used in electric vehicles and autonomous power systems.

Another promising option is a fuel cell-supercapacitor structure. In this structure, the fuel cell serves as the primary source of energy, providing a stable voltage and long-term power, while the supercapacitor compensates for dynamic power fluctuations, ensuring a rapid response during load changes or start-up. This structure is particularly effective in both transport and stationary systems, where quiet operation, high efficiency, and zero emissions are required. The fuel cell operates in a steady state with high efficiency, while the supercapacitor absorbs short-term peak currents, thereby reducing membrane degradation and enhancing the durability of the entire system.

In industrial and network applications, battery-flywheel or battery-CAES/PHS structures are also utilised, providing a balance between energy capacity and power. Passive topologies of such systems are the simplest but limited in control, while semi-active and fully active ones allow optimising energy distribution between subsystems.

In general, the fuel cell-supercapacitor structure is considered one of the most promising areas of HESS development for autonomous transport and microgrids, as it combines continuous power supply, high power and environmental friendliness. Further research is focused on improving the efficiency of converters and implementing intelligent control systems that provide adaptive interaction between the source and the storage device.

The traction drive system comprises an electromechanical complex that includes a brushless DC motor, a control system, and a hybrid energy storage system consisting of a fuel cell and a supercapacitor. All elements of the power system are connected to a common DC bus via controlled DC-DC converters, which ensure optimal energy distribution between power sources and loads.

The fuel cell is the main source of energy, providing stable power to the system in steady-state vehicle modes. It is characterised by high energy capacity, but has a relatively slow response time. To compensate for short-term peak loads associated with acceleration, braking or changing driving conditions, a supercapacitor with high specific power and low time constant is introduced into the system.

Controlled DC-DC converters serve to match voltage levels between energy sources and a common DC bus. Depending on the drive mode (acceleration, braking, steady motion), the control system distributes energy flows between the fuel cell, supercapacitor and motor. During braking, excess recuperation energy is directed to the supercapacitor, thereby increasing the system's energy efficiency and reducing the load on the fuel cell.

On the load side, the DC bus powers an inverter that generates three-phase AC voltage to power the brushless motor. The inverter also controls the torque and speed of the motor via pulse width modulation (PWM) in accordance with the controller signals. The electric drive system controller implements an energy management algorithm that takes into account the state of charge of the supercapacitor, the power of the fuel cell and the drive requirements.

The electrical diagram of the transport electric drive system is shown in Fig. 1. It demonstrates the interaction between the fuel cell, supercapacitor, DC-DC converters, DC bus, switch and brushless motor. This structure ensures high efficiency, reliability and flexibility in the operation of the transport electric drive, which is especially important for electric vehicles and specialised vehicles.

To model a hydrogen fuel cell in a hybrid energy storage system, a simplified electrical model was used that takes into account key electrochemical losses but does not describe complex mass transfer processes and electrode reaction dynamics. The output voltage of a single fuel cell element is determined by the equation:

$$V_{\mathrm{fc}}(I) = E_{\mathrm{N}} - V_{\mathrm{act}}(I) - V_{\mathrm{ohm}}(I) - V_{\mathrm{cont}}(I)\,, \tag{1}$$

where E_N is the thermodynamic electromotive force, $V_{act}(I)$ is the activation loss resulting from the kinetics of electrochemical reactions at the electrodes, $V_{ohm}(I)$ is the ohmic loss associated with the voltage drop across the internal resistance of the membrane and electrodes, $V_{cont}(I)$ is the concentration losses caused by the limitation of mass transfer of reagents during cell operation.

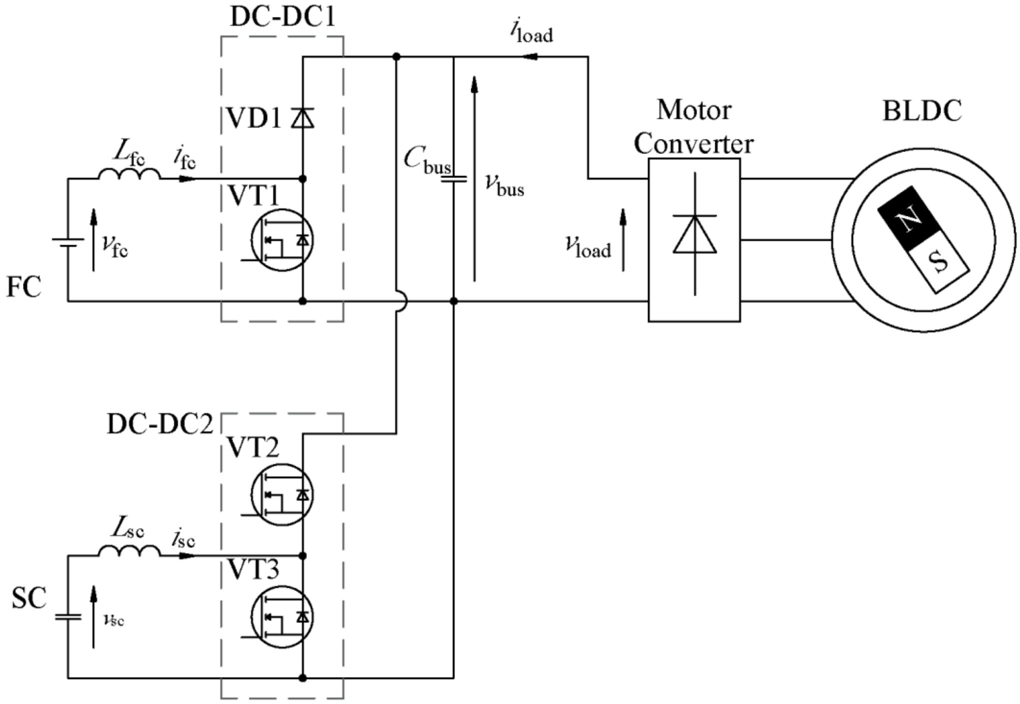

Fig. 1. Electrical diagram of the transport drive system

This model provides a description of the static electrical characteristics of FC and enables its effective integration into the overall model of a hybrid energy storage system without significantly complicating the calculations [26]. For energy-shaping control synthesis, in this work, FC will be modelled as a voltage source $v_{fc} = V_{fc}(I)$, and the mathematical model of its internal process will be hidden under this abstraction and used only in the simulation model.

Control of DC–DC converters in electric drive systems or hybrid energy storage systems is carried out by an energy-shaping control system, whose main function is to stabilise the voltage across the DC bus according to the system's energy requirements. The voltage reference is determined by the output of the PI speed controller, which generates the required energy command based on the error between the reference and actual angular speed of the electric motor. Thus, the energy-shaping subsystem coordinates the dynamics of the DC-link electrical circuit with the mechanical subsystem of the drive, ensuring stable motor operation under various load conditions.

The use of a cascaded control structure in such systems is justified by both physical considerations and control theory. The separation of the system into an outer speed-control loop and an inner DC-voltage-control loop makes it possible to take into account the difference in inertia between the mechanical and electrical subsystems. The electrical subsystem, characterised by high responsiveness, reacts quickly to load variations and stabilises the voltage, while the slower mechanical loop defines the long-term system dynamics. This organisation enhances the closed-loop system's stability, improves its transient performance, and ensures proper energy flow coordination between the power sources, energy storage devices, and the motor.

The cascaded principle also minimises current surges and energy losses, since controllers at different hierarchical levels perform complementary tasks. In complex hybrid systems incorporating fuel cells and supercapacitors, such a structure enables efficient energy distribution: the fuel cell provides the steady-state power, while the supercapacitor compensates for fast load fluctuations. Moreover, the cascaded approach is consistent with the principles of energy-based control methodologies such as Passivity-Based Control (PBC) and Interconnection and Damping Assignment PBC (IDA-PBC), in which the inner loop shapes the desired interconnections between power flows and the outer loop regulates the system's total energy. This approach ensures high accuracy, robustness, and energy efficiency in dynamic operating conditions of hybrid electromechanical systems.

The mathematical model of the control object of the inner loop is formed based on Kirchhoff's laws for each element that acts as an energy accumulator, namely, inductance coils and capacitors. After writing down the differential equations for these elements, the following mathematical model was obtained [23]:

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}t} v_{\mathrm{bus}} = \dfrac{1}{C_{\mathrm{bus}}} \left[\mu_{\mathrm{fc}} i_{\mathrm{fc}} + \mu_{\mathrm{fc}} i_{\mathrm{fc}} - i_{\mathrm{load}} \right] \\ \dfrac{\mathrm{d}}{\mathrm{d}t} i_{\mathrm{fc}} = \dfrac{1}{L_{\mathrm{fc}}} \left[(v_{\mathrm{fc}} - \mu_{\mathrm{fc}} v_{\mathrm{bus}} \right] \\ \dfrac{\mathrm{d}}{\mathrm{d}t} i_{\mathrm{sc}} = \dfrac{1}{L_{\mathrm{sc}}} \left[(v_{\mathrm{sc}} - \mu_{\mathrm{sc}} v_{\mathrm{bus}} \right] \\ \dfrac{\mathrm{d}}{\mathrm{d}t} v_{\mathrm{sc}} = -\dfrac{i_{\mathrm{sc}}}{\mathrm{C}_{\mathrm{sc}}} \end{cases} \tag{2}$$

where i and v are the currents and voltages of the corresponding circuit elements.

When applying the PBC-method for energy-shaping control system (ESCS) synthesis, the control object must be considered as a port-controlled Hamilton system (PCH), which has the following form [24]:

$$\dot{\mathbf{x}}(t) = \left[\mathbf{J}(\mathbf{x}) - \mathbf{R}(\mathbf{x}) \right] \nabla H(\mathbf{x}) + \mathbf{G}(\mathbf{x})\, \mathbf{u}(t) \tag{3}$$

where $\mathbf{x}(t)$ is the state variable vector, $\mathbf{J}(\mathbf{x})$ is the asymmetric interconnection matrix, $\mathbf{R}(\mathbf{x})$ is the semi-definite symmetric damping matrix, $H(\mathbf{x})$ is the system energy accumulation function (Hamiltonian), $\mathbf{D}$ is the diagonal matrix of inertias, $\mathbf{G}(\mathbf{x})$ is the input port matrix, $\mathbf{u}(t)$ is the vector of input variables of the system.

The main vectors and matrices for describing the hybrid FC-SC HESS as PCH are as follows:

$$\mathbf{x} = [C_{\mathrm{bus}} v_{\mathrm{bus}} \quad L_{\mathrm{fc}} i_{\mathrm{fc}} \quad L_{\mathrm{sc}} i_{\mathrm{sc}} \quad C_{\mathrm{sc}} v_{\mathrm{sc}}]^{\mathrm{T}}; \tag{4}$$

$$\mathbf{u} = \left[-i_{\mathrm{load}} \quad v_{\mathrm{fc}} \quad 0 \quad 0 \right]^{\mathrm{T}}; \tag{5}$$

$$\mathbf{D} = \mathrm{diag} \left[C_{\mathrm{bus}} \quad L_{\mathrm{fc}} \quad L_{\mathrm{sc}} \quad C_{\mathrm{sc}} \right]; \tag{6}$$

$$\mathbf{y} = [v_{\mathrm{bus}} \quad i_{\mathrm{fc}} \quad i_{\mathrm{sc}} \quad v_{\mathrm{sc}}]^{\mathrm{T}}. \tag{7}$$

Based on (4) and (6), the total energy function of the system and the vector of its partial derivatives are as follows:

$$H(\mathbf{x}) = \frac{1}{2} \mathbf{x}^{\mathrm{T}} \mathbf{D}^{-1} \mathbf{x} = \frac{1}{2} \left(C_{\mathrm{bus}} v_{\mathrm{bus}}{}^2 + L_{\mathrm{fc}} i_{\mathrm{fc}}{}^2 + L_{\mathrm{sc}} i_{\mathrm{sc}}{}^2 + C_{\mathrm{sc}} v_{\mathrm{sc}}{}^2 \right); \tag{8}$$

$$\nabla H(\mathbf{x}) = \frac{\partial H(\mathbf{x})}{\partial \mathbf{x}} = \mathbf{D}^{-1} \mathbf{x} = [v_{\mathrm{bus}} \quad i_{\mathrm{fc}} \quad i_{\mathrm{sc}} \quad v_{\mathrm{sc}}]^{\mathrm{T}}. \tag{9}$$

The PCH structure matrices of this system, taking into account (2) - (9), are as follows:

$$\mathbf{J}=\begin{bmatrix} 0 & \mu_{\mathrm{fc}} & \mu_{\mathrm{sc}} & 0 \\ -\mu_{\mathrm{fc}} & 0 & 0 & 0 \\ -\mu_{\mathrm{sc}} & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}; \qquad (10)$$

$$\mathbf{R}=\mathrm{diag}\begin{bmatrix}0 & 0 & 0 & 0\end{bmatrix}; \qquad (11)$$

$$\mathbf{G}=\mathrm{diag}\begin{bmatrix}1 & 1 & 0 & 0\end{bmatrix}. \qquad (12)$$

The PBC-IDA method consists of ensuring the desired level of total system energy by purposefully forming the necessary interconnections and damping. The goal of this approach is to build control influence formers (CIF) that ensure the movement of a closed system to a given equilibrium point with predetermined dynamic properties.

The specified equilibrium point is determined by the control function and corresponds to the desired total energy function H_{d}, which at the same time acts as the target optimisation function – at this point, it assumes its minimum value.

In this case, the dynamics of the closed system are described by the following vector-matrix equation:

$$\tilde{\mathbf{x}}(t)=\left[\mathbf{J}_{\mathrm{d}}(\tilde{\mathbf{x}})-\mathbf{R}_{\mathrm{d}}(\tilde{\mathbf{x}})\right]\ \nabla H_{\mathrm{d}}(\tilde{\mathbf{x}}). \qquad (13)$$

where $H_{\mathrm{d}}(\tilde{\mathbf{x}})=0.5\,\tilde{\mathbf{x}}^{\mathrm{T}}\mathbf{D}\tilde{\mathbf{x}}$, and $\tilde{\mathbf{x}}=\mathbf{x}-\bar{\mathbf{x}}$ – a new state vector is formed as the difference between the current coordinates and their specified (equilibrium) values. To achieve the desired connections and damping in the subsystem, additional elements are introduced, which are expressed by equations (13):

$$\mathbf{J}_{\mathbf{d}}=\mathbf{J}+\mathbf{J}_{\mathbf{a}},\ \ \mathbf{R}_{\mathbf{d}}=\mathbf{R}+\mathbf{R}_{\mathbf{a}}, \qquad (14)$$

where $\mathbf{J_a}$ and $\mathbf{R_a}$ are matrices of interconnections and damping that implement control influences and determine the structure of the control system.

The structural synthesis of asymptotically stable PBC systems boils down to finding such forms of matrices $\mathbf{J_a}$ and $\mathbf{R_a}$ that ensure the identity between equations (3) and (13). This task is solved using a symbolic solution of vector-matrix equations in the MathCad environment according to the author's methodology [25].

To synthesise a PBC control system for the speed of an electric transport drive with a BLDC motor, a vector of steady-state coordinates is formed in the form (15), where V_{bus}^* is the desired value of the DC bus voltage formed by the PI speed controller and fed to the ESCS input, and V_{sc}^* is the preferred value of the supercapacitor voltage. The index '0' denotes the steady-state values of the state variables obtained as a result of structural synthesis. The pulse filling coefficients μ_{fc} and μ_{sc}, together with the variables i_{fc} and i_{sc}, determine the structure of the control influence shaper, which characterises the synthesised PBC system of the electric drive.

$$\bar{\mathbf{x}}=\begin{bmatrix}V_{\mathrm{bus}}^* & i_{\mathrm{fc0}} & i_{\mathrm{sc0}} & V_{\mathrm{sc}}^*\end{bmatrix}. \qquad (15)$$

The complete matrices of relationships and damping for ESCS are given below:

$$\mathbf{J_a}=\begin{bmatrix} 0 & j_{12} & j_{13} & j_{14} \\ -j_{12} & 0 & j_{23} & j_{24} \\ -j_{13} & -j_{23} & 0 & j_{34} \\ -j_{14} & -j_{24} & -j_{34} & 0 \end{bmatrix}, \qquad (16)$$

$$\mathbf{R_a} = \mathrm{diag}\left[r_{11} \quad r_{22} \quad r_{33} \quad r_{44} \right]. \tag{17}$$

As a result of the synthesis of the ESCS PCH electric drive, matrices (12) and (13) have 10 independent additional interconnections $\mathbf{j_a}$ and dampings r_a, which make it possible to form multiple CIFs for the traction electric drive system. As a result of research using computer simulation, the CIF structures shown in Table 1 were selected.

Table 1

Selected CIF structures

CIF Group 1	CIF Group 2
$\mu_{sc} = \dfrac{V_{sc}^*}{V_{bus}^*}$ $\mu_{fc} = \dfrac{v_{fc}}{V_{bus}^*}$ (18)	$\mu_{sc} = \dfrac{V_{sc}^*}{V_{bus}^*}$ $\mu_{fc} = \dfrac{v_{fc}}{V_{bus}^*} + j_{12}\dfrac{v_{bus} - V_{bus}^*}{V_{bus}^*}$ (19)
CIF Group 3	**CIF Group 4**
$\mu_{sc} = \dfrac{V_{sc}^*}{V_{bus}^*} + j_{13}\dfrac{v_{bus} - V_{bus}^*}{V_{bus}^*}$ $\mu_{fc} = \dfrac{v_{fc}}{V_{bus}^*}$ (20)	$\mu_{sc} = \dfrac{V_{sc}^*}{V_{bus}^*} + j_{13}\dfrac{v_{bus} - V_{bus}^*}{V_{bus}^*}$ $\mu_{fc} = \dfrac{v_{fc}}{V_{bus}^*} + j_{12}\dfrac{v_{bus} - V_{bus}^*}{V_{bus}^*}$ (21)
CIF Group 5	
$\mu_{sc} = \dfrac{V_{sc}^*}{V_{bus}^*} + r_{33}\left(-\dfrac{i_{sc}}{V_{bus}^*}\right)$ $\mu_{fc} = \dfrac{v_{fc}}{V_{bus}^*}$ (22)	

Further parametric synthesis of controllers and research in MATLAB/Simulink environment were carried out according to the computer model shown in Fig. 2.

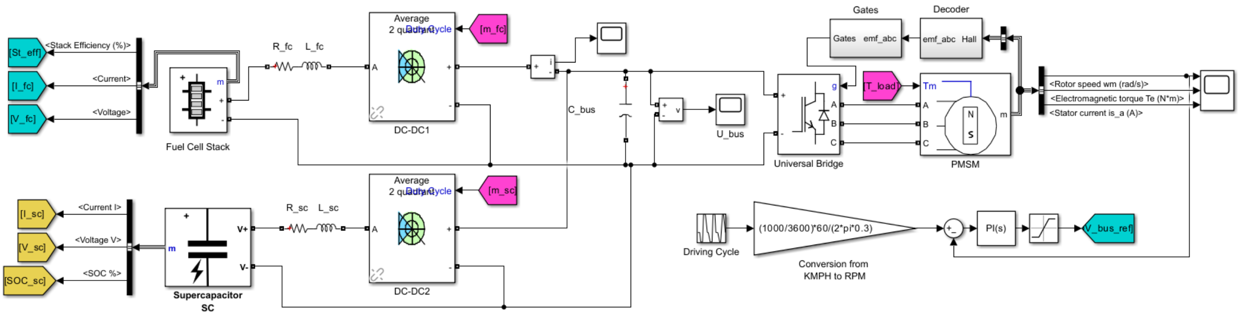

Fig.2. Computer model of a cascaded electric transport drive system with BLDC

In the computer modelling of a cascade control system for an electric transport drive with BLDC, elements with the following parameters were used:

FC: type – PEMFC-50kW-625Vdc, rated voltage – 625 V, rated current – 80 A.

BLDC: number of phases – 3, number of poles – 8, rated voltage – 560 V, rated speed – 3000 rpm, rated torque – 111 N· m, rated power – 34.86 kW, moment of inertia – 0.011 kg/m2.

SC: rated capacity – 214.3 F, equivalent resistance 0.118 Ohm, rated voltage 561.6 V.

After performing parametric synthesis and testing the resulting CIFs on a computer model, the most effective CIF group was found to be 3, which utilises the j_{13} interconnection, responsible for the influence of i_{fc} on v_{bus} and changes the FC load, respectively. The coefficient allows for increasing and decreasing the FC load and, accordingly, increasing the SC load. This can be especially useful at high loads and high dynamics. Studies of other additionally introduced interconnections and damping have shown that damping r_{33} forces the transient processes of FC and SC currents, mainly due to the increase of i_{fc}. Interconnection j_{12} acts opposite to j_{13}, by switching the load from SC to FC. The remaining CIF structures delay the transient process of motor acceleration, lead system to instability or make it difficult to balance. It is also worth mentioning that the use of CIF Group 5 can be extended with interconnection j_{14} and damping r_{33}, which are responsible for the transient processes of v_{sc} and its influence on v_{bus}, allowing for extended energy management strategies.

When the interaction coefficient j_{13} increases, the FC assumes a larger share of the energy demand, providing power under steady-state or slowly varying load conditions (Fig. 3). This mode is optimal when high energy efficiency is required and no rapid dynamic changes occur. A greater contribution from the FC stabilises the DC bus voltage v_{bus}, reducing the need for frequent deep SC cycles and extending the overall lifetime of the energy storage system.

Conversely, when the influence of j_{13} is intentionally reduced, the system transitions into a supercapacitor-dominated mode. In this case, the FC contribution to bus voltage regulation weakens, and most of the energy flow is supplied by the SC. This mode is crucial during sudden load changes, acceleration, or peak pulse demands. Due to its low internal resistance and high dynamic response, the SC instantly compensates voltage drops and ensures stable motor operation without the inertial delays inherent to the FC.

Thus, through the interconnection j_{13}, the electric drive system can smoothly and adaptively shift priority between sources—from an energy-efficient mode dominated by the FC to a high-dynamic mode dominated by the SC. This eliminates abrupt transitions between operating states, maintains v_{bus} stability, and ensures the optimal balance between dynamics, efficiency, and overall reliability of the electric drive.

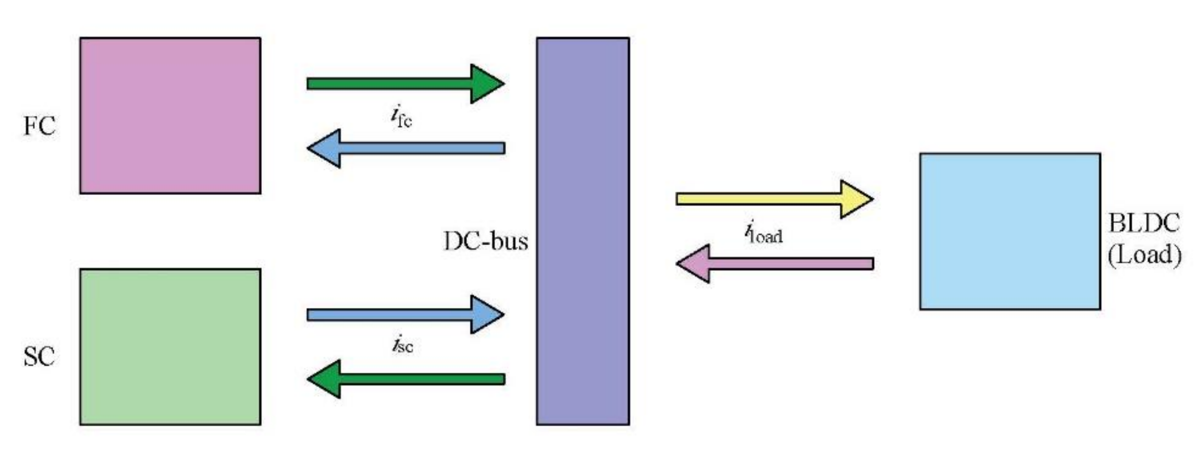

Fig.3. Functional diagram of energy flow formation in the electric drive system

The results of computer modelling obtained using CIF 1 and CIF 3 groups are shown in Figure 4. As a result of parametric synthesis of control systems, the value of the coefficient j_{13} for the CIF 3 group (19) was set at 1.5. The criteria for parametric synthesis were set to achieve the highest system performance with the least overshoot of the step response. Two disturbing factors act on the system: the system setpoint signal ω* and the static load torque on the motor. The BLDC angular velocity reference signal, in the form of a transport lifecycle, is shown in Fig. 4, together with the results obtained for both control systems. The static load torque acts on the system with a nominal value of the electromagnetic torque of the motor of 111 N·m.

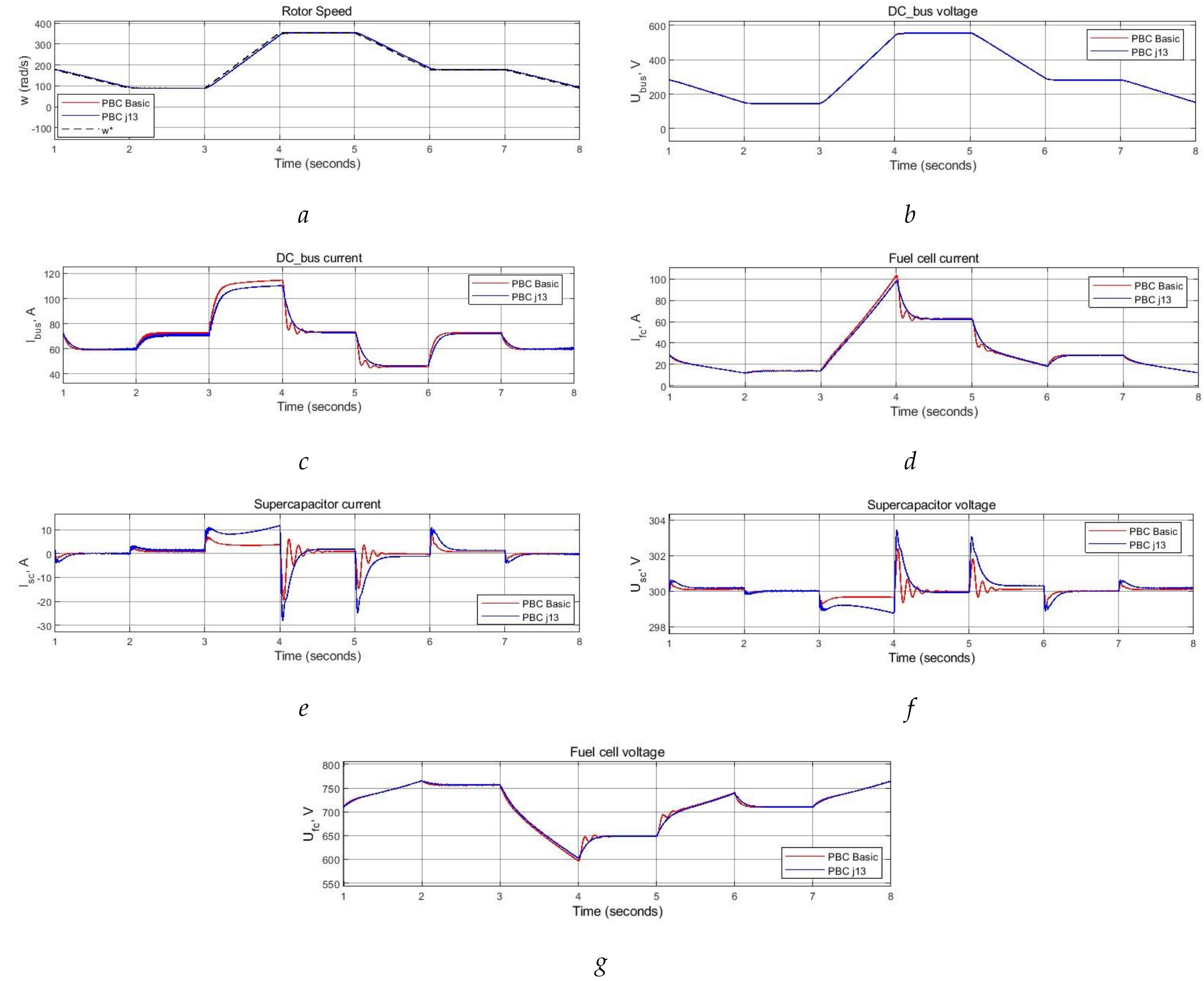

Fig. 4. Simulation results: a) angular velocity of the motor w, b) DC bus voltage v_{bus}, c) current i_{bus}, d) current through the fuel cell i_{fc}, e) current through the supercapacitor i_{sc}, f) voltage across the supercapacitor v_{sc}, g) voltage across the fuel cell v_{fc}.

Based on the obtained oscillograms, it should be noted that the use of an additional relationship between the DC bus voltage and the current through the supercapacitor reduces the fluctuations of the main energy variables of the system, while ensuring a minimum error in the response of the task signal to the system (Fig. 4, a). This indicates an increase in the coordination between the energy flow subsystems, as well as the effective operation of the regulators within the energy-shaping control structure. The ibus current when using the CIF 3 group changes smoothly and is characterised by a lower speed (Fig. 4, c). This behaviour indicates improved energy interaction between the power sources and the load, as well as effective compensation of peak currents by the supercapacitor. The current through the fuel cell (Fig. 4, d) has a smooth, virtually oscillation-free dynamics, which is desirable in terms of the resource and stability of the fuel cell. Similarly, the current through the supercapacitor (Fig. 4, e) does not contain short-term fluctuations, but there is a slight increase in its average value in steady states. This indicates an increase in the degree of involvement of the supercapacitor in the process of stabilising the DC bus voltage, as well as a redistribution of energy flows between sources within the electric vehicle's on-board network. The voltages across the fuel cell (Fig. 4, g) and supercapacitor (Fig. 4, f) have a similar variation pattern to the corresponding currents through these elements. This confirms the correctness of the constructed model, the consistency of the dynamics of the energy links, and the effectiveness of the implemented control structure, which ensures the energy consistency of the subsystems and the stability of the system during transient processes.

Conclusions

The paper presents the results of research on a control system for the electric drive of a vehicle powered by a hybrid energy storage system combining a fuel cell and a supercapacitor, connected by a common DC bus via controlled DC-DC converters. The energy analysis and modelling confirmed the effectiveness of the chosen architecture, which distributes functions between the sources: the fuel cell serves as the primary energy source, while the supercapacitor serves as a power source, compensating for peak loads and contributing to efficient energy recovery.

The proposed cascade combination of energy-shaping control and a PI speed regulator ensures the coordination of subsystem dynamics, eliminates current oscillations in the DC bus, and achieves the desired transient characteristics of the entire system. The use of an additional j_{13} interconnection between the bus voltage and the supercapacitor current reduces the pulsations of the main energy variables and stabilises the operation of the electric drive under variable load conditions.

The results obtained indicate the feasibility of using a combined ‘fuel cell-supercapacitor’ architecture in transport systems with an energy-shaping control principle. This approach ensures the dynamic stability and operational reliability of the electric drive, enabling the development of advanced control actions for the electric drive system through the formation of desired interconnections and damping, which enhances the system’s resilience to external disturbances.

As a direction for further research, a comparative analysis of the drive characteristics is planned for various architectures of the onboard power supply system of the electric drive, different power ratios of its constituent elements, and varying degrees of involvement of the energy-shaping control system in the drive control.

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Energy-shapping cascade control of a traction electric drive system with a hybrid power source

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ЕНЕРГОФОРМУЮЧЕ КАСКАДНЕ КЕРУВАННЯ СИСТЕМОЮ ТЯГОВОГО ЕЛЕКТРОПРИВОДУ З ГІБРИДНИМ ДЖЕРЕЛОМ ЖИВЛЕННЯ

У статті представлено структуру та принципи роботи системи електроприводу транспортного засобу з гібридною системою нагромадження енергії, що поєднує паливну комірку та суперконденсатор, з’єднані через керовані DC–DC перетворювачі зі спільною шиною постійного струму. Функції тягового приводу виконує безщітковий двигун постійного струму (BLDC) що живиться трифазною напругою від інвертора приєднаного до DC-шини. Паливна комірка є основним джерелом енергії, забезпечуючи стабільну роботу системи в номінальних режимах, тоді як суперконденсатор компенсує пікові навантаження, покращує динаміку та підвищує ефективність рекуперації.

У роботі обґрунтовано вибір архітектури гібридної паливно-суперконденсаторної системи нагромадження енергії, проведено аналіз потоків енергії та взаємодії між компонентами через керовані DC–DC перетворювачі. Особливу увагу приділено реалізації енергоформуючого принципу керування в каскаді з ПІ-регулятором швидкості, який забезпечує узгодження динаміки джерел енергії, продовження ресурсу паливної комірки і відпрацювання завдань приводу. Запропонований підхід орієнтований на підвищення керованості системи та покращення стійкості приводу під час перехідних процесів.

Результати дослідження підтверджують доцільність використання комбінованої архітектури «паливна комірка – суперконденсатор» у транспортних електроприводах з енергоформуючим керуванням. Така система забезпечує високу ефективність, стабільність напруги у спільній шині постійного струму, швидку реакцію на зміни навантаження та розширює можливості рекуперації енергії під час гальмування.

Ключові слова: транспортний засіб, паливна комірка, суперконденсатор, гібридна система нагромадження енергії, безщітковий двигун постійного струму, каскадне керування, енергоформуюче керування.