

Development of a Control System for an Electric Fuel Pump for an Ultra-Light Launch Vehicle [†]

Kenzhebek Myrzabekov ^{1,*}, Kuanysh Alipbayev ¹, Akylbek Bapyshev ², Teodor Iliev ³ and Alina Fazylova ¹

¹ Department of Aerospace and Electronic Engineering, Almaty University of Power Engineering and Telecommunications Named After Gumarbek Daukeyev, Almaty 050013, Kazakhstan; k.alipbayev@aes.kz (K.A.); a.fazylova@aes.kz (A.F.)

² Department of Electronics, Telecommunications and Space Technologies, Kazakh National Research Technical University named after K.I. Satpayev, Almaty 050013, Kazakhstan; akylbek.bapyshev@gmail.com

³ Department of Telecommunications, University of Ruse, 8 Studentska Str., 7004 Ruse, Bulgaria; tiliev@uni-ruse.bg

* Correspondence: k.myrzabekov@aes.kz; Tel.: +7-(776)-929-0000

[†] Presented at the International Conference on Electronics, Engineering Physics and Earth Science (EEPES2026), Bandirma, Turkey, 24–27 June 2026.

Abstract

This article discusses the development of a control system for an electric propellant pump for a light-lift launch vehicle. The relevance of this work stems from the need to create compact and energy-efficient propellant supply systems capable of ensuring stable operation within the weight, size, and energy resource constraints of onboard equipment. The research object is presented as a single electromechanical-hydraulic system comprising an electric drive, a pump unit, a hydraulic circuit, and a digital control system. A mathematical model of the electric pump unit is developed, its numerical parameterization is performed, and a cascade control structure with a feedforward channel is proposed. A series of computational experiments are conducted, including an analysis of transient processes during pressure target changes, a study of the system's response to hydraulic disturbances, and a robustness assessment under parameter uncertainty. It is established that the proposed control system provides higher response speed, a smaller integral control error, and better resistance to external disturbances compared to a classical cascade PI structure. The obtained results confirm the potential of the proposed approach for electric pump units for fuel supply of ultra-light launch vehicles.

Keywords: ultra-light launch vehicle; electric propellant pump; control system; cascade PI control; numerical modeling; transient processes



Academic Editors: Ivaylo Stoyanov,
Grigor Mihaylov and
Selahattin Kosunalp

Published: 3 September 2026

Copyright: © 2026 by the authors.
Licensee MDPI, Basel, Switzerland.
This article is an open access article
distributed under the terms and
conditions of the [Creative Commons
Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Modern developments in space technology are characterized by a steadily growing interest in small and ultra-light launch vehicles, focused on delivering lightweight payloads, rapidly accessing orbit, and reducing launch costs. Under these conditions, compact and energy-efficient propellant delivery systems capable of providing an acceptable balance between weight, reliability, complexity, and controllability of the propulsion system are particularly relevant. One of the most promising areas in this area is the use of an electric pump delivery system, in which the pump is driven by an electric motor rather than a gas turbine unit. As demonstrated in [1], an electrically driven pump system can be considered a competitive alternative to traditional gas generator systems, particularly in applications

where layout simplicity, a reduction in the number of auxiliary components, and the ability to flexibly adjust the engine operating mode are critical.

Recent studies [2–6] confirm the practical relevance of electrically driven pump-fed propellant systems for small launch vehicles and show that control quality strongly depends on the coupled dynamics of the electric drive, pump, and hydraulic line. However, studies focused specifically on control-oriented modeling and comparative controller analysis for ultra-light launch vehicles remain limited. Therefore, the objective of this study is to develop a mathematical model and control system for an electric propellant pump for an ultra-light launch vehicle, followed by a numerical evaluation of its dynamic characteristics in transient and disturbed modes.

The novelty of the study lies in the use of a unified electromechanical-hydraulic model for synthesizing and comparing cascaded control strategies for pressure regulation under command and disturbance variations.

In contrast to conventional industrial pumping systems and larger rocket propulsion applications, the considered ultra-light launch vehicle case is characterized by a combination of severe mass, volume, and onboard power constraints, short-duration transient operating modes, and limited margins for pressure instability in the propellant feed line. Therefore, the control system must provide fast pressure regulation and disturbance rejection without relying on heavy auxiliary components or complex actuation hardware. This application-specific combination of compactness, rapid response, and energy-limited operation distinguishes the proposed control problem from general electric pump control tasks and defines the practical relevance of the developed control structure.

2. Materials and Methods

The object of this study is a control system for an electric propellant pump designed for use on a light-lift launch vehicle. This class of launch vehicles is characterized by strict limitations on weight, power consumption, and the dimensions of onboard systems [7]. Therefore, the development of a compact and energy-efficient electric pump unit with stable automatic regulation of propellant delivery parameters is of particular importance. The general structure of the system under study is shown in Figure 1. The diagram shows the main components of the electric pump unit: a fuel tank, an oxidizer tank, a fuel pump with an electric motor, pressure and flow sensors, a control unit, a power converter, and the propellant supply line to the propulsion system. This diagram illustrates the general operating principle of the system, in which propellant from the tank is delivered to the engine using an electric pump, and the required pressure and flow parameters are maintained by a closed-loop automatic control system.

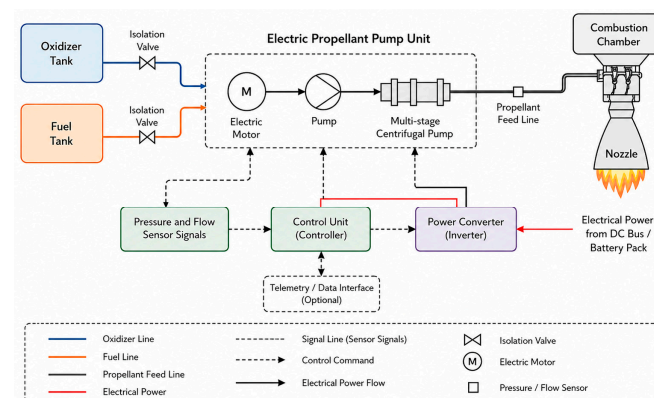


Figure 1. System architecture diagram of the electric propellant pump unit and control system for an ultra-light launch vehicle.

Thus, the electric pump unit is considered as an electromechanical-hydraulic system combining an electric drive, a pump section, a hydraulic circuit, and a digital control system. The primary objective of the system is to maintain a specified fuel delivery mode in the presence of parametric and external disturbances. The block diagram of the control system is shown in Figure 2. It includes pressure and speed setpoints, regulators, a pulse-width control unit, an electric motor, a fuel pump, a feedback loop for measured parameters, and a limiting and protection unit. As shown in Figure 2, the control system is constructed using the cascade principle. The outer loop generates the required fuel pressure value, and the inner loop regulates the rotational speed of the electric motor directly connected to the pump. Feedback is provided using data from the pressure p , angular velocity ω , and current I sensors. The limiting and protection unit allows for the consideration of current, pressure, and rotational speed limits, which is especially important for onboard rocket systems.

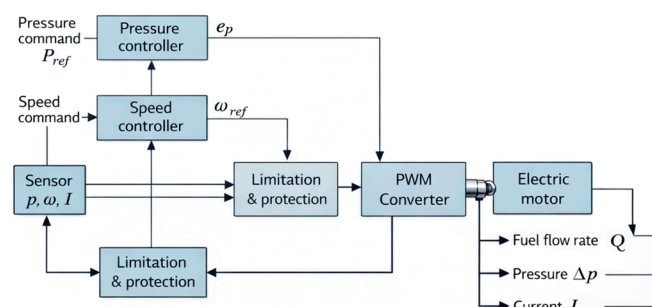


Figure 2. Block diagram of the cascaded control system for the electric propellant pump.

The choice of a cascade structure was determined by the difference in the characteristic times of the processes in the system. Electrical and mechanical processes in the drive occur faster than hydraulic processes in the fuel supply line, so a dual-loop control arrangement improves stability and control quality.

The study is based on a control-oriented electromechanical-hydraulic model of the electric pump unit, including the electric motor, pump, hydraulic line, and feedback control loops. The model parameters were taken from the motor data, nominal pump operating point, and hydraulic-line assumptions used for numerical simulation.

This approach made it possible to study the influence of control actions and external disturbances on the stability of fuel delivery and determine a rational control system structure for a super-light launch vehicle.

The electric motor of the electric pump unit was described by a system of electrical and mechanical equilibrium equations. For the electrical component, the following equation was used [8]:

$$L \frac{di}{dt} + Ri + k_e \omega = u, \quad (1)$$

where L denotes motor winding inductance, R denotes active resistance of the winding, i denotes current, k_e denotes back-EMF coefficient, ω denotes rotor angular velocity, and u denotes control voltage.

The electromagnetic torque of the engine was determined by the expression [9]:

$$M_e = k_t i, \quad (2)$$

where k_t is the torque constant and i is the motor current.

The rotor dynamics were described by the mechanical equilibrium equation [10]:

$$J \frac{d\omega}{dt} = M_e - M_p - M_f, \quad (3)$$

where J is the reduced moment of inertia, M_p is the pump's moment of resistance, and M_f is the moment of friction and mechanical resistance losses.

The pump unit's performance was determined by the rotor speed and the pressure drop in the system. Generally, fuel consumption was described by the equation [11]:

$$Q = k_q \omega - k_l \Delta p, \quad (4)$$

where Q is the fuel flow rate, k_q is the pump performance coefficient, k_l is the hydraulic loss and leakage coefficient, and Δp is the pressure drop.

The change in pressure in the line, taking into account the compressibility of the working fluid, was described by the following relationship [12]:

$$\frac{d(\Delta p)}{dt} = \frac{\beta_e}{V} (Q - Q_L), \quad (5)$$

where β_e is the effective bulk modulus of the fuel, V is the reduced volume of the hydraulic system, and Q_L is the flow rate due to the load.

The load was considered to be an equivalent section of the fuel supply line to the engine. In the simplest approximation, the flow rate due to the load was described by the relationship [13]:

$$Q_L = C_d A \sqrt{\frac{2\Delta p}{\rho}}, \quad (6)$$

where C_d is the flow coefficient, A is the equivalent cross-sectional area, and ρ is the fuel density.

Thus, the final system model integrates the electrical, mechanical, and hydraulic subsystems and enables the analysis of transient processes in the electric pump unit as a single, interconnected control object.

Taking into account the structure shown in Figure 2, a cascade electric pump control system is adopted in this study. The outer loop is designed to stabilize the fuel pressure, and the inner loop is designed to regulate the electric motor speed. The pressure control error was determined as [14]:

$$e_p = p_{ref} - p, \quad (7)$$

where p_{ref} denotes set pressure and p is current measured pressure.

The speed control error was determined as:

$$e_\omega = \omega_{ref} - \omega, \quad (8)$$

where ω_{ref} is set rotation speed and ω is the current rotor speed.

A cascaded PI control structure was used, with the outer loop regulating pressure and the inner loop regulating motor speed. For the proposed variant, a feedforward channel was added.

The feedforward component was introduced to compensate for the expected pressure-command variation and to generate a preliminary motor-speed reference before feedback correction. In this study, the speed reference for the inner loop was defined as

$$\omega_{ref}(t) = \omega_{PI}(t) + K_{ff} (p_{ref}(t) - p_0), \quad (9)$$

where $\omega_{PI}(t)$ is the pressure-controller output, K_{ff} is the feedforward gain, $p_{ref}(t)$ is the pressure command, and p_0 is the nominal pressure.

The control system included actuator saturation and protection limits for voltage, current, speed, and pressure. The numerical study considered command changes, hydraulic-load disturbances, and voltage variations representative of ultra-light launch vehicle operation. The main performance indicators were settling time, integral absolute error, and pressure-drop depth under disturbance [14]. The model was parameterized around the nominal operating point to ensure a single consistent basis for comparing the conventional cascaded PI controller and the proposed cascaded PI controller with feedforward. The numerical parameterization was performed for a nominal pump speed of 30,000 rpm. The remaining coefficients were derived from the nominal operating point, similarity relations, hydraulic compliance assumptions, and motor data [15]. The adopted values are summarized in Table 1.

Table 1. Summary of the adopted numerical parameters of the electric pump-fed propellant supply model.

Parameter	Symbol	Value	Unit	Basis for Adoption
Nominal rotor speed	n_0	30,000	rpm	Adopted operating point
Nominal angular speed	ω_0	3141.59	rad/s	Calculated from n_0
Fuel density	ρ	800.98	kg/m ³	Working-fluid property
Nominal pressure rise	Δp_0	5.799×10^5	Pa	Pump similarity scaling
Nominal mass flow rate	$\dot{m}_0$	3.768×10^{-2}	kg/s	Pump similarity scaling
Nominal volumetric flow rate	Q_0	4.704×10^{-5}	m ³ /s	$Q_0 = \dot{m}_0 / \rho$
Armature resistance	R	0.363	Ω	Motor datasheet
Armature inductance	L	4.9×10^{-5}	H	Motor datasheet
Back-EMF constant	K_e	7.83×10^{-3}	V·s/rad	Motor datasheet
Torque constant	K_t	7.85×10^{-3}	N·m/A	Motor datasheet
Rotor inertia	J	4.20×10^{-7}	kg·m ²	Motor datasheet
Viscous friction coefficient	B	6.33×10^{-7}	N·m·s/rad	Identified from no-load regime
Pump efficiency	η_p	0.6727	—	Adopted pump characteristic
Flow coefficient	k_q	1.497×10^{-8}	m ³ /rad	Derived from Q_0, ω_0
Pressure coefficient	k_p	5.876×10^{-2}	Pa·s ² /rad ²	Derived from $\Delta p_0, \omega_0$
Pump load coefficient	c_p	1.308×10^{-9}	N·m·s ² /rad ²	Power balance
Load coefficient	K_L	4.948×10^{-5}	kg·s ⁻¹ ·Pa ^{-1/2}	Nominal load matching
Effective bulk modulus	β_{eff}	0.984×10^9	Pa	Adopted hydraulic parameter
Effective hydraulic volume	V_{eff}	3.30×10^{-3}	m ³	Adopted hydraulic parameter
Hydraulic compliance coefficient	α_h	2.98×10^{11}	Pa/m ³	β_{eff} / V_{eff}
Maximum control voltage	u_{max}	36	V	Drive limitation

For the robustness assessment, the main electrical and hydraulic parameters were varied around their nominal values: armature resistance R by $\pm 20\%$, armature inductance L , back-EMF constant K_e , and torque constant K_t by $\pm 10\%$, effective bulk modulus β_e by $\pm 25\%$, and hydraulic load coefficient C_L by $\pm 20\%$.

The controller gains used in the numerical experiments were $K_{p,p} = 9000$, $K_{i,p} = 35,000$, $K_{p,\omega} = 0.06$, and $K_{i,\omega} = 80$ for the conventional cascaded PI controller, and $K_{p,p} = 12,000$, $K_{i,p} = 60,000$, $K_{p,\omega} = 0.12$, and $K_{i,\omega} = 180$ for the proposed cascaded PI controller with feedforward.

3. Results and Discussion

Numerical simulation was performed in Python 3.13.5 using a unified nonlinear electromechanical-hydraulic model and the same parameter set for all computational scenarios. Only the command amplitude and disturbance conditions were varied between experiments. Control performance was evaluated by settling time, integral absolute error, and pressure-drop depth under disturbance.

Figure 3 compares the transient processes for two control options: a classic cascade PI structure and the proposed cascade PI system with a feedforward channel. In the representative combined scenario, the proposed controller demonstrates higher performance. The settling time decreases from 0.087 s to 0.028 s, the integral absolute error decreases from 0.0138 to 0.0085 MPa·s, and the pressure-drop depth decreases from 4.64% to 3.56%. This improvement is explained by partial compensation of the plant dynamics through the feedforward channel, which reduces the burden on the feedback loop.

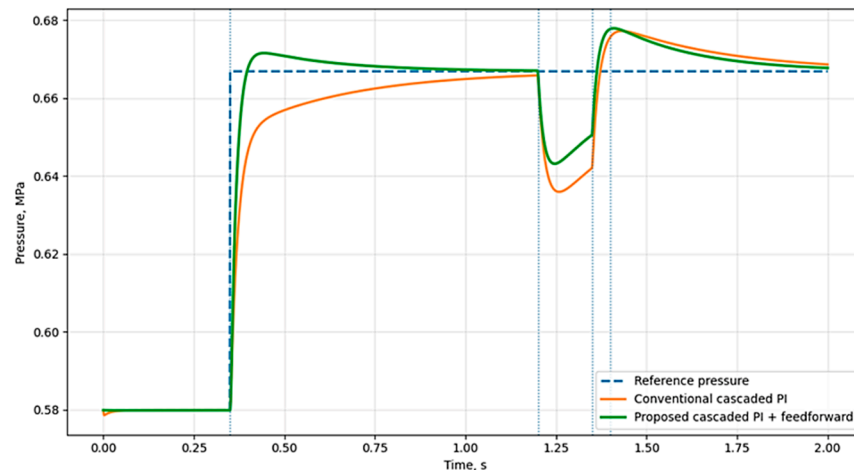


Figure 3. Comparative transient response under a severe command-and-disturbance scenario.

Figure 3 also shows that the advantage of the proposed controller is not limited to the initial command-tracking interval. After the hydraulic disturbance is introduced, the pressure deviation is smaller and the recovery process is shorter than in the classical cascaded PI case. This behavior is important for ultra-light launch vehicles, where even short pressure deviations may affect the stability of propellant delivery and the repeatability of the engine operating regime. The feedforward channel improves the coordination between the pressure command and the required motor-speed response, thereby reducing the delay between the hydraulic demand and the actuator reaction.

The quantitative results presented in Figure 4 show that for the classical cascade PI structure, the settling time increases from 0.025 s for a 5% step to 0.133 s for a 20% step. For the proposed algorithm, this indicator changes significantly less—from 0.014 s to 0.031 s.

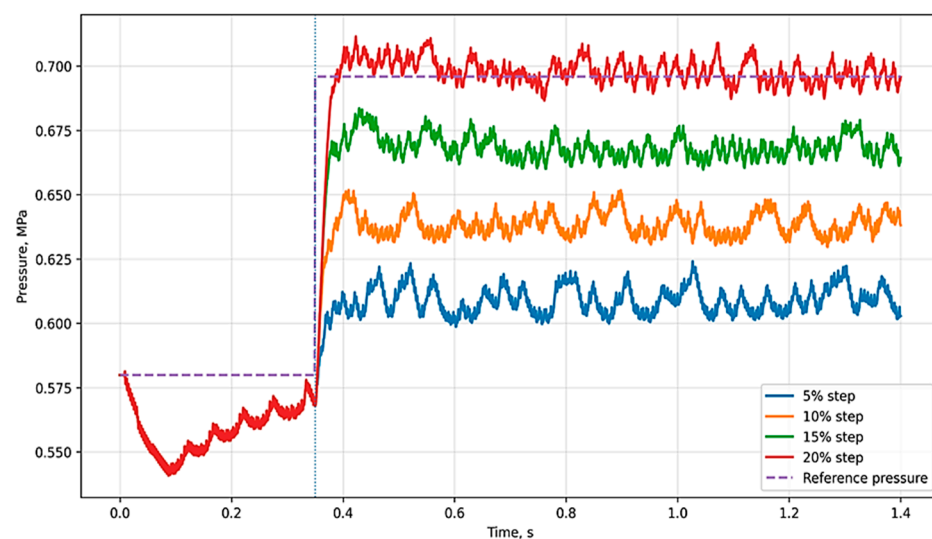


Figure 4. Settling time as a function of the pressure-command step amplitude.

Thus, the proposed controller preserves a clear dynamic advantage over the full investigated command range.

Figure 5 shows the transient pressure responses of the proposed algorithm at different hydraulic-load disturbance levels. As the disturbance amplitude increases, the pressure drop becomes more pronounced, but the closed-loop system remains stable and restores the pressure to the commanded level without sustained oscillations. This result indicates that the proposed control structure maintains adequate damping and robustness over the investigated disturbance range. From an application perspective, this behavior is important because the hydraulic resistance of the propellant feed line may vary during transient engine operation, and the control system must compensate for such variations without excessive pressure undershoot. The small high-frequency fluctuations visible in Figures 4 and 5 are associated with the nonlinear closed-loop simulation and discretized control action. They were not introduced as explicit sensor noise or PWM-induced ripple, but they indicate possible control-induced pressure ripple that should be limited in practical implementation to reduce additional mechanical and thermal loading on the actuator.

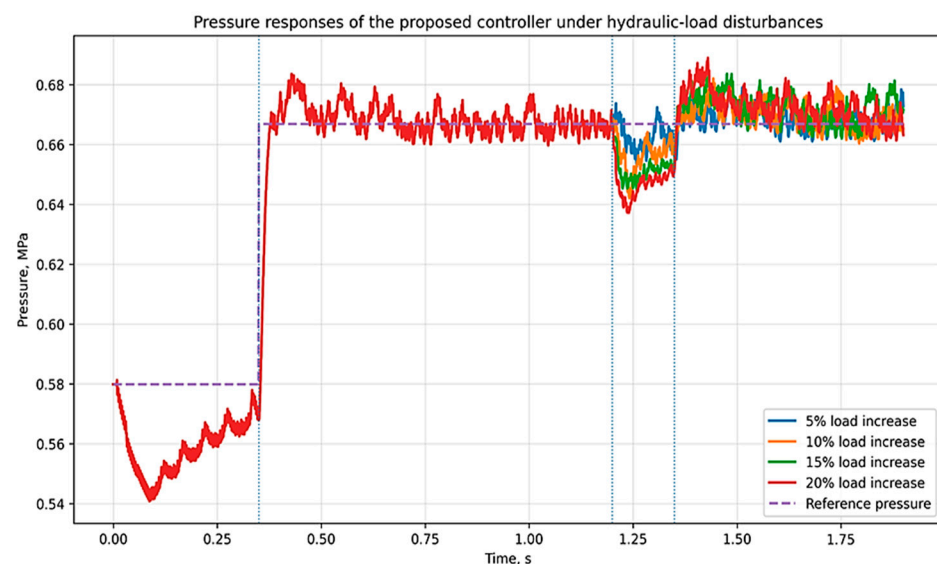


Figure 5. Pressure responses of the proposed controller under hydraulic-load disturbances.

Calculations showed that for the classical algorithm, the pressure drop is 2.03%, 3.90%, 5.73%, and 7.53% for 5%, 10%, 15%, and 20% disturbances, respectively. For the proposed structure, the corresponding values are reduced to 1.48%, 2.97%, 4.43%, and 5.87%. The reduction in pressure-drop depth is about 21–27%, confirming improved disturbance rejection. Figure 6 shows that the IAE gain is maintained throughout the entire computational domain and ranges from approximately 15% to 64%.

In the practically relevant region of the operating domain, the improvement is typically 30–46%, indicating that the performance gain is systematic rather than local.

Overall, the proposed cascaded PI controller with feedforward provides faster response, lower integral error, and better disturbance rejection across the investigated operating range.

From the viewpoint of ultra-light launch vehicle constraints, the reduced pressure overshoot and faster settling time can also contribute to more efficient use of onboard electrical power. By decreasing the duration and amplitude of transient deviations, the proposed controller may reduce unnecessary motor acceleration, current peaks, and overshoot-related power demand. This is important for electric pump-fed propulsion systems, where the battery pack, power converter, and thermal margins are strongly limited by mass and volume constraints.

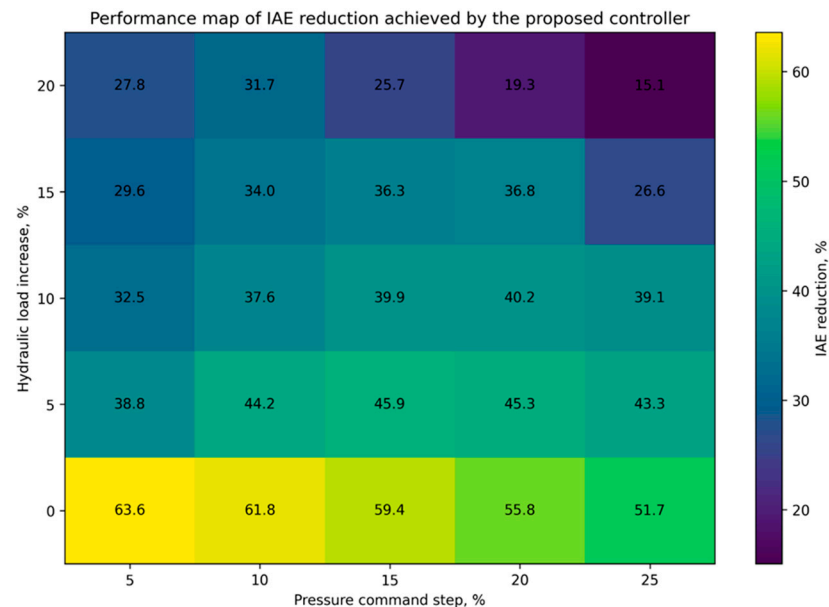


Figure 6. Performance map of IAE reduction achieved by the proposed controller.

4. Conclusions

This paper develops a control system for an electric propellant pump for a light-lift launch vehicle based on a unified electromechanical-hydraulic model. Computational experiments demonstrated that the proposed cascade PI structure with a leading channel provides superior control quality compared to a conventional cascade PI controller. In the most representative combined mode, the settling time decreased from 0.087 s to 0.028 s, the integral absolute error decreased from 0.0138 to 0.0085 MPa s, and the pressure-drop depth during a disturbance decreased from 4.64% to 3.56%. Furthermore, in the studied range of operating conditions, the integral error decreased from 15% to 64%, confirming the consistent performance of the proposed algorithm not only at a single computational point but also across a wide range of operating conditions. The obtained results confirm the operability, robustness and practical potential of the proposed control system for electric pump units for fuel supply of ultra-light launch vehicles.

Author Contributions: Conceptualization, K.M., K.A. and A.F.; methodology, A.B.; software, K.M.; validation, K.A., A.F. and T.I.; formal analysis, A.B.; investigation, A.F.; resources, K.M.; data curation, A.B.; writing—original draft preparation, K.M.; writing—review and editing, K.M.; visualization, T.I.; supervision, K.A.; project administration, K.A.; funding acquisition, K.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, grant number BR27195331.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data generated in this study are presented in the article. For any clarifications, please contact the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kwak, H.-D.; Kwon, S.; Choi, C.-H. Performance assessment of electrically driven pump-fed LOX/kerosene cycle rocket engine: Comparison with gas generator cycle. *Aerosp. Sci. Technol.* **2018**, *75*, 335–343. [\[CrossRef\]](#)
2. Zhou, C.; Yu, N.; Wang, J.; Cai, G. Starting and Regulating Characteristics of Electric Pump Feed System for LRE under Different Schemes. *Appl. Sci.* **2022**, *12*, 6441. [\[CrossRef\]](#)
3. Myrzabekov, K.; Alipbayev, K.; Bapyshev, A.; Kozhabek, Z.; Kaliyeva, N.; Nogaibayeva, M. Methodology for Selecting an Electric Pump and Battery Pack for a Low-Thrust LRE: Computational Simulation Study. *Eng. Proc.* **2026**, *122*, 6. [\[CrossRef\]](#)
4. Gu, X.; Tian, H.; Tan, G.; Liang, T.; Wang, J.; Meng, X.; Cai, G. The filling process and its effect on the start-up of electric pump in hybrid rocket motor. *Acta Astronaut.* **2023**, *211*, 216–228. [\[CrossRef\]](#)
5. Casalino, L.; Masseni, F.; Pastrone, D. Viability of an Electrically Driven Pump-Fed Hybrid Rocket for Small Launcher Upper Stages. *Aerospace* **2019**, *6*, 36. [\[CrossRef\]](#)
6. Sun, M.; Long, X.; Xu, B.; Ding, H.; Wu, X.; Yang, W.; Zhao, W.; Liu, S. Review of Thrust Regulation and System Control Methods of Variable-Thrust Liquid Rocket Engines in Space Drones. *Actuators* **2025**, *14*, 385. [\[CrossRef\]](#)
7. Moldabekov, M.M.; Orazaly, Y.Y.; Aden, A.Y. Construction of the Stability Region of the Rocket Angular Stabilization System by the Coefficient Method. In *Advances in Asian Mechanism and Machine Science*; Tuleshov, A., Jomartov, A., Ceccarelli, M., Eds.; Mechanisms and Machine Science; Springer: Cham, Switzerland, 2024; Volume 167, pp. 414–421. [\[CrossRef\]](#)
8. Jafari, M.; Reyhanoglu, M.; Kozhabek, Z. Simple Learning-Based Robust Nonlinear Control of an Electric Pump for Liquid-Propellant Rocket Engines. *Electronics* **2023**, *12*, 3527. [\[CrossRef\]](#)
9. Zhou, C.; Yu, N.; Cai, G.; Wang, J. Comparison between the dynamic characteristics of electric pump fed engine and expander cycle engine. *Aerosp. Sci. Technol.* **2022**, *124*, 107508. [\[CrossRef\]](#)
10. Kim, G.Y.; Lee, H.J.; Huh, H. Experimental study on flow control system of an electric pump-fed cycle for thrust control. *Acta Astronaut.* **2024**, *216*, 44–54. [\[CrossRef\]](#)
11. Fazylova, A.; Iliev, T.; Stoyanov, I.; Siemens, E. Height Control System for Wind Turbines Based on Critical Wind Speed Calculation. *Appl. Sci.* **2024**, *14*, 9802. [\[CrossRef\]](#)
12. Tian, H.; Gu, X.; Wang, J.; Tan, G.; Liang, T.; Cai, G. The effect of pipeline length on the transient process of an electric pump during start-up of a hybrid rocket motor. *Acta Astronaut.* **2023**, *210*, 1–10. [\[CrossRef\]](#)
13. Cui, P.; Li, Q.; Cheng, P.; Chen, L. System scheme design for LOX/LCH₄ variable thrust liquid rocket engines using motor pump. *Acta Astronaut.* **2020**, *171*, 120–130. [\[CrossRef\]](#)
14. Fazylova, A.; Alipbayev, K.; Iliev, T.; Aden, A. Advanced Control Strategies for Wind Turbine Blade Pitch Optimization. In *Proceedings of the 5th IEEE International Conference on Communications, Information, Electronic and Energy Systems (CIEES 2024)*; IEEE: New York, NY, USA, 2024. [\[CrossRef\]](#)
15. Gu, X.; Tian, H.; Wang, J.; Liang, T.; Wei, T.; Niu, X.; Cai, G. Operational instability of a high-rotational-speed electric pump in a hybrid rocket motor. *Aerosp. Sci. Technol.* **2023**, *141*, 108496. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.