POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2025 ✦ Volume 28 ✦ Issue 3 ✦ 27–50

DOI: 10.33223/epj/205944

Vadym Reva[1], Kostyantyn Zemlyanyi[2], Oleksandr Udovyk[3], Oleksii Leonov[4], Maciej Jamiński[5], Dariusz Sala[6]

Comprehensive study of power supply systems for space rocket complexes with emphasis on control and power quality management

Abstract: This research addresses the growing challenges posed by the increasing power demands of modern Space Rocket Complexes (SRCs), particularly in relation to integrating various types of electrical consumers. As SRC systems become more complex, ensuring electromagnetic compatibility and maintaining electric power quality are now critical and economically significant issues. The main objective of the study is to develop an algorithm for the optimal selection of power supply system (PSS) structures for SRCs, with a strong focus on electric power quality management. Several PSS configurations were analyzed and compared, each evaluated for reliability, control efficiency, and adaptability to operational conditions. A systematic algorithm and corresponding block diagram

✉ Corresponding Author: Vadym Reva; e-mail: reva.vad@ukr.net

[1] "Pivdenne" State Design Office, Ukraine; ORCID iD: 0000-0002-1104-8398; e-mail: reva.vad@ukr.net

[2] "Pivdenne" State Design Office, Ukraine; ORCID iD: 0000-0001-5043-3566; e-mail: zemlyany.konstantin@gmai.com

[3] Dnipro University of Technology, Ukraine; ORCID iD: 0009-0002-1000-7815; e-mail: Udovyk.O.V@nmu.one

[4] Dnipro University of Technology, Ukraine; ORCID iD: 0009-0009-3680-9542; e-mail: Leonov.O.S@nmu.one

[5] AGH University of Science and Technology in Krakow, Poland; ORCID iD: 0000-0003-4416-5598; e-mail: sala@agh.edu.pl)

[6] AGH University of Science and Technology in Krakow, Poland; ORCID iD: 0000-0003-1246-2045; e-mail: mjaminski@agh.edu.pl

were created to guide the selection process, integrating power quality parameters into early design decisions. The methodology was tested using the Cyclone-4 launch complex as a case study. Within this framework, a prototype electric power quality control system was designed and partially implemented. Experimental testing validated the effectiveness of the proposed approach, confirming that early integration of power quality considerations significantly enhances system reliability and economic performance. Key findings emphasize the importance of incorporating power quality criteria into SRC infrastructure planning to ensure stable operation under complex and variable conditions. This study ultimately contributes to the development of more robust and efficient power systems for future space missions. It offers a structured and practical approach for selecting and managing power supply systems in high-demand aerospace environments, emphasizing the value of proactive quality control and comprehensive system design.

KEYWORDS: Power Supply Systems (PSS), Space Rocket Complexes (SRC), energy, electricity quality indicators

Introduction

The Cyclone-4 space rocket complexes (SRC), developed by Ukraine for Brazil, and the Cyclone-4M for Canada, are characterized by increased total power consumption and higher equipment costs associated with the technological operations of launch vehicle preparation. This results in stricter requirements for the design and implementation of power supply systems (PSS), ensuring the efficient operation of electrical equipment. Developers must focus on optimizing power distribution and enhancing system reliability to meet these demands (Kuznietsov 2024). Advanced control mechanisms are essential for maintaining stability and efficiency under varying operational conditions. The integration of modern energy management technologies plays a crucial role in minimizing power losses and improving overall system performance (Gladky and Perlik 2000). The complexity of these space systems necessitates rigorous testing and validation of PSS components to prevent failures during critical launch phases (Hladkyi 2020). As a result, ongoing innovation and refinement in power supply technologies remain essential for the successful deployment of these advanced rocket complexes.

An analysis of the existing SRC and their power supply systems highlighted the main advantages and disadvantages of such systems. The main feature of these systems is that they were designed over a long period, without taking into account the features of modern cyclograms for Integrated Launch Vehicle (ILV) preparation, as outlined in regulatory documents (EN 50160:2022). The drawbacks include the lack of systematic quality control in typical power supply systems, which will be presented in Section 3 of this research. Previously created complexes, such as SRC Dnepr, SRC Zenit, Soyuz, etc., contain elements of automation and protection without system quality control. However, they still do not fully provide a high-quality power supply to the complex, and do not provide for all kinds of emergencies in power supply systems (Kuznietsov 2024; Gladky and Perlik 2000; Linnik 2021).

The main criteria that PSS must comply with are the reliability and reliability of its operation. Possible emergency and abnormal situations that occur in power supply systems and subsequently lead to a partial or complete interruption of ILV preparation and its subsequent start-up are associated with indicators of electricity quality (Hladkyi 2020). The quality of electricity, according to DSTU (EN 50160:2022; IEEE 1547-2003), refers to the degree of compliance of the electricity parameters with their established values.

Starting from the design stage of PSS, in the modern designed air distribution systems (such as Cyclon-4, Cyclon-4M, etc.), a special part was introduced and optimized as part of the PSS – the electric power quality control system (EPQCS), which allows controlling everything power quality indicators, identify and prevent possible emergencies and partially manage the power supply system. The provision and control of the quality of electricity is one of the important tasks of the power supply systems of the SRC, considered at the initial stage of creating the SRC.

1. Reference background for the power supply systems for space rocket complexes

The research on the analysis and selection of power supply systems (PSS) for space rocket complexes (SRCs) is highly relevant due to the increasing energy demands and stringent reliability requirements of modern space missions. As launch vehicle technology advances, the complexity of power distribution, control, and quality management becomes a critical factor in ensuring mission success (Kuznietsov 2024; Fedoreiko et al. 2014). Efficient PSS must not only provide stable and uninterrupted power to various subsystems but also incorporate advanced control mechanisms to adapt to dynamic operational conditions (Fedoreiko et al. 2014; Dychkovskyi et al. 2019). The growing use of automation, digital monitoring, and innovative energy management solutions underscores the need for optimized PSS designs that minimize power losses, enhance system resilience, and reduce operational costs (Kuznietsov 2024; Linnik 2021; Pivnyak et al. 2024). Furthermore, as space agencies and private aerospace companies push for more cost-effective and sustainable launch solutions, research in this area contributes to improving energy efficiency, safety, and overall performance. This study plays a vital role in developing innovative approaches to power management that align with the evolving requirements of next-generation space exploration programs.

In recent years, Europe has significantly advanced its space technology capabilities, with increased cooperation under the European Space Agency (ESA) framework and growing national efforts from member states such as Poland. Poland's involvement in space initiatives has intensified since joining ESA in 2012, contributing to projects in satellite systems, propulsion, and space infrastructure development. The Polish Space Agency (POLSA) has played a key role in fostering innovation and supporting partnerships between government, academia, and industry, aligning national strategies with the broader objectives of ESA and the European Union

(POLSA 2020). Notably, Poland's participation in programs such as Copernicus and Galileo has elevated its position in Earth observation and navigation technologies. Meanwhile, investment in domestic startups and R&D centers reflects a commitment to building independent space capabilities (Wachowicz 2022). These developments are indicative of a broader European trend toward strategic autonomy in space, focusing on both civil and defence-related applications (ESPI 2023).

The efficient and reliable power supply of SRCs is crucial for their successful operation, necessitating high precision, stability, and resilience under extreme conditions (Pivnyak et al. 2024; Polyanska et al. 2024a). A modern trend in power supply focuses on optimizing energy use within the framework of a culture of frugal energy consumption, ensuring minimal energy waste while maintaining operational excellence (Pivnyak et al. 2024; Polyanska et al. 2024b). Given the growing demand for sustainable energy management, integrating advanced energy storage systems, thermoelectric solutions, and hybrid power architecture is crucial for enhancing the reliability and efficiency of SRCs (Gladky and Perlik 2000; Nikolsky et al. 2020).

SRC power systems experience rapid load variations due to the high-energy demands of propulsion, launch sequences, and onboard systems (Lofstrom 1985). These dynamic modes involve transient phenomena such as voltage fluctuations, harmonic distortions, and reactive power imbalances, which require precise control and compensation mechanisms (Lofstrom 1985; Richert et al. 2024). Advanced quality management strategies, including active filtering and real-time monitoring, ensure that power parameters remain within critical limits, preventing failures that could jeopardize mission success (Lofstrom 1985; Golovchenko et al. 2020).

Using different transformers plays a vital role in SRC power distribution, enabling efficient voltage regulation and the separation of subsystems (Lofstrom 1985; Seheda et al. 2024). These transformers experience complex electromagnetic interactions, including transient overvoltage, eddy currents, and thermal effects. Optimizing their design enhances energy efficiency and minimizes power losses, ensuring stable SRC operations. Innovations such as superconducting windings and AI-driven predictive maintenance further enhance reliability and reduce downtime (Seheda et al. 2024; Papaika et al. 2024).

The thermodynamic challenges in SRC power systems include managing contact heating, where high-energy electrical contacts experience rapid temperature spikes, leading to material degradation (Lofstrom 1985; Papaika et al. 2024; Sobolev et al. 2024). Effectively handling heat dissipation requires advanced cooling techniques, such as phase-change materials and liquid metal interfaces (Seheda et al. 2024; Fedoreiko et al. 2013). Understanding these thermal dynamics is crucial for designing components that withstand extreme conditions, ensuring long-term reliability, and reducing maintenance costs.

SRC environments involve translational-rotational motion of incompressible, dense plasma temperatures formed under shock waves, significantly affecting electrical conductivity and insulation properties (Lofstrom 1985; Seheda et al. 2024; Sobolev et al. 2024). The chemical interactions of gas molecules during movement influence ionization levels and plasma behavior. These factors are critical in propulsion systems, plasma-based energy conversion, and electromagnetic shielding, requiring precise modeling and control to optimize SRC power system management (Sobolev et al. 2024; Wessler 1986).

A combined and zero-waste gasifier offers a novel approach to generating auxiliary power for SRC infrastructure by utilizing waste gases from propulsion systems or fuel processing (Lofstrom 1985; Tabachenko et al. 2016). By integrating gasification with fuel cells or thermoelectric generators, power systems can achieve higher efficiency and lower emissions (Seheda et al. 2024; Dychkovskyi et al. 2024). These hybrid systems support SRCs in remote locations, enhancing energy self-sufficiency and reducing dependence on external power grids (Wessler 1986; Kosenko et al. 2024).

The integration of electric vehicles (EVs) and thermoelectric modules into SRC support systems further enhances energy efficiency and sustainability (Dychkovskyi et al. 2024; Dudek 2014). EVs facilitate logistics within space launch facilities, reducing reliance on fossil fuels, while thermoelectric modules capture waste heat from propulsion and power conversion processes, improving overall energy utilization (Seheda et al. 2024; Bennett et al. 2001). Such advancements contribute to a comprehensive culture of frugal energy consumption, optimizing both environmental and operational aspects of SRC power systems (Polyanska et al. 2024b; Sandhu et al. 1999).

The implementation of simulations for a "dry run" significantly helps operators when familiarizing themselves with the software, instrumentation, and any tools used to carry out the work. Additionally, it enables potential problems to be identified even before the actual processes are implemented, thereby minimizing the risk of costly errors. The results also help solution providers further improve the tools they use, enabling them better to adapt their functionality to the actual needs of users. Regular testing and optimization of simulations contribute to increased operational efficiency and improved occupational safety (Kumawat et al. 2023; Misljenovic et al. 2023).

Combining RES with energy storage systems and intelligent energy management can significantly improve power quality and stability. Advanced control strategies and optimisation frameworks are needed to manage energy variability under conditions of varying demand. The development of renewable energy technologies creates new opportunities to stabilise the grid and increase the share of green energy in power systems. The use of hybrid RES systems enables different sources to complement each other, thereby reducing the impact of their natural variability on the stability of supply (Mahmood et al. 2024; Das et al. 2024).

This research aligns with contemporary demands for energy-efficient, sustainable, and high-performance power supply solutions, ensuring that space missions operate with optimal energy management and minimal waste.

2. Methods and methodology of power supply for space rocket complexes research

The research on power supply methods for space rocket complexes, with integrated provision control and quality management of electric power, is based on a systematic and multidisciplinary approach (Kuznietsov, 2024; Gladky and Perlik 2000; Pivnyak et al. 2024; Sandhu et al. 1999). The study employs analytical, experimental, and simulation-based methodologies to evaluate the efficiency, stability, and reliability of power systems in space launch infrastructure (Gladky and Perlik 2000; Lofstrom 1985; Wessler 1986; Sandhu et al. 1999). A key focus is placed on redundancy mechanisms, smart grid integration, and adaptive control algorithms to mitigate fluctuations and ensure a continuous power supply. Computational modelling using well-known software such as MATLAB/Simulink and PSCAD is utilized to simulate electrical load variations and transient responses under different operational scenarios. Experimental verification is conducted using high-precision power quality analysers to assess voltage stability, harmonic distortions, and electromagnetic interference, ensuring compliance with aerospace standards.

The methodology incorporates a risk-based assessment aligned with ISO 9001 and ISO 50001 quality management frameworks to optimize energy efficiency and reliability. Fault-tolerant control strategies, including real-time monitoring through SCADA systems, are employed to enhance the resilience of the power infrastructure (EN 50160:2022; IEEE 1547-2003; Kannu et al. 2003). The research also integrates renewable energy sources and energy storage systems to improve sustainability and reduce dependency on conventional power grids. By applying data-driven decision-making and predictive analytics, the study enhances fault diagnostics and preventive maintenance strategies. The overall methodology ensures a high-quality power supply essential for the safe and efficient operation of space rocket complexes.

2.1. Formation of various structures in the power supply system of SRC

The greater the weight of the rocket, the more electricity is consumed in the preparation and launch of this rocket. A feature of the applied electrical receivers is their variety and complexity, which is expressed in the fact that, along with the traditional three-phase and single-phase loads in the form of synchronous and asynchronous motors, air conditioning and lighting systems, they have a large proportion of receivers with a pronounced non-linear load: rectifiers, various static converters, power supplies with transformer less input, as well as power receivers of electronic computers and other technical means of information technology.

When constructing the power supply system of the ground complex from the internal power supply system, various structures are used (Kannu et al. 2003). This can be a power supply system for technological equipment, guaranteed power supply systems, etc. The power supply system of technological equipment (PSS TE) is designed to provide the required power supply to technological equipment with the specified type and quality of electric power in all system operating modes (Kannu et al. 2003; Reva et al. 2025).

The guaranteed power supply system (GPSS), utilizing the IPSS of the ground-based complex, is designed to provide electricity with a specified voltage and frequency to critical technological equipment (the most demanding power consumers) in the first category of reliability (Group 1A) across all modes of complex operation.

The following PSS structures (Fig. 1, 2, 3) are centralized, distributed (localized), and two-level for the power supply of critical PSS consumers. The centralized system contains one UPS, to which all responsible consumers are connected. In a distributed system, each consumer (or group of local consumers) is powered by a separate (local) UPS (Hajji et al. 2020; Frolov 2010).

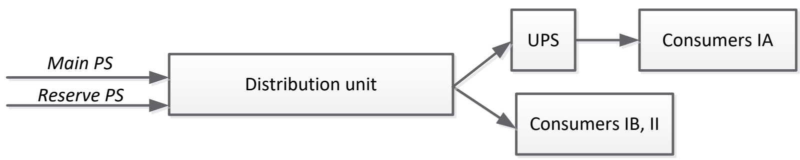

Fig. 1. Distributed structure of PSS

Rys. 1. Rozproszona struktura PSS

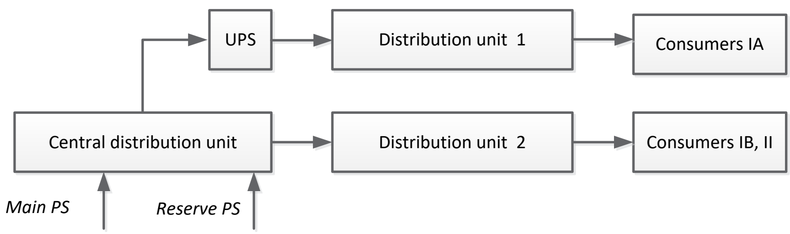

Fig. 2. Centralized structure of PSS

Rys. 2. Scentralizowana struktura PSS

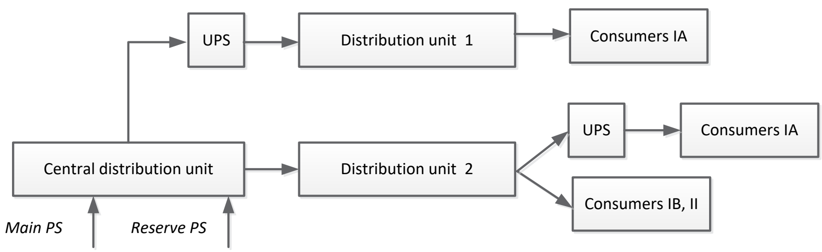

Fig. 3. Two-level structure of PSS

Rys. 3. Dwupoziomowa struktura PSS

The centralized system consists of a single uninterruptible power supply (UPS) that provides backup power to all critical consumers, ensuring a stable and continuous energy supply (Fig. 2). While this approach simplifies power management, it creates a single point of failure, which can compromise the entire system in case of a UPS malfunction. In contrast, the distributed system assigns a separate (local) UPS to each consumer or a group of local consumers, thereby increasing reliability and reducing the risk of total system failure (Fig. 1). However, this method requires a higher initial investment and more complex maintenance due to the multiple independent power sources. To mitigate the drawbacks of both centralized and distributed approaches, a two-level system is commonly implemented in practice (Fig. 3). This hybrid configuration integrates elements of both structures, enhancing redundancy, reliability, and operational efficiency. By strategically balancing power distribution and backup capabilities, the two-level system ensures optimal performance while minimizing risks associated with power supply disruptions.

In existing space rocket complexes, power supply systems include separate components that, to varying degrees, regulate power quality indicators. However, these individual elements operate independently, limiting their overall effectiveness in ensuring stable and efficient power distribution. A comprehensive analysis of current power supply systems, considering their operational modes and structural characteristics, has highlighted the need for a more integrated approach to power supply systems. This approach should focus on developing a unified system for monitoring power quality and optimizing energy management. Implementing such a system will enhance reliability, improve efficiency, and ensure compliance with stringent aerospace power standards.

2.2. Mathematical apparatus for electricity quality indicators and formulas

A significant problem of the normal functioning of power supply systems of space rocket complexes, as well as any power supply system, given the relatively rapid growth rate of the number of converter and microprocessor equipment of various types in electrical networks, the problem of electromagnetic compatibility and power quality (PQ) becomes relevant (Flores 2002). PQ characterizes the electromagnetic environment in which the equipment connected to the PQ operates. The economic aspect most fully illustrates this; for example, the annual economic loss to the world energy industry due to low power quality is approximately $500 billion per year (Flores 2002; Pivnyak et al. 2021), mainly due to the negative impact of asymmetric and non-sinusoidal voltage fluctuations.

In the considered PSS structures, standards establish eleven indicators of electricity quality. The specifics of the ground-based complex for PSS are as follows: high and low voltage, high voltage pulses, harmonic distortion of the pulse voltage, unstable frequency, and voltage dips. The reduced quality of electricity has a negative impact on both the work of individual consumers and the normal functioning of the system.

A low level of quality of electric energy leads to a decrease in the energy efficiency of electric networks, including due to an increase in losses of active and reactive capacities, technological expenses of electric energy for its transport, to a decrease in the service life of electrical equipment, an increase in capital investments, and violation of the conditions for the normal functioning of the energy system.

Electricity parameters are described by the following formulas (Stones and Collinson 2001; Białobrzeski et al. 2024; Dugan 2004):

- voltage deviation:

$$\delta U(t) = \frac{U(t) - U_H}{U_H} \cdot 100\% \tag{1}$$

where:

$U(t)$, U_H – current and normal voltage;

- effective value of interphase voltages:

$$U(t) = \frac{1}{3}\left(U_{AB(1)} + U_{BC(1)} + U_{AC(1)}\right) \tag{2}$$

where:

$U_{AB(1)}$, $U_{BC(1)}$, $U_{AC(1)}$ – effective values of interfacial voltages of the fundamental frequency;

- voltage swing range (ripple factor):

$$\delta U_i = \frac{|U_i - U_{i+1}|}{U_H} \cdot 100\% \tag{3}$$

where:

U_i, U_{i+1} – values of voltage extremes;

- voltage curve non-sinusoidality coefficient:

$$k_{HCU} = \frac{1}{U_H}\sqrt{\sum\nolimits_{n=2}^{N} U_n^2} \cdot 100\% \tag{4}$$

where:

U_H – the effective value of the n-th harmonic component of the voltage,
N – order of the last of the considered harmonics;

✦ reverse sequence voltage coefficient:

$$k_{2U} = \frac{U_{2(1)}}{U_H} \cdot 100\% \tag{5}$$

where:

$U_{2(1)}$ – the effective value of the voltage of the negative sequence of the fundamental frequency of the three-phase voltage system:

$$U_{2(1)} = \frac{\sqrt{3(U_{A(1)}Y_A + U_{B(1)}Y_B + U_{C(1)}Y_C)}}{Y_A + Y_B + Y_C} \tag{6}$$

where:

Y_A, Y_B, Y_C – phase conductivity A, B, C;

✦ zero sequence voltage coefficient:

$$k_{0U} = \frac{U_{0(1)}}{U_{H.\Phi.}} \cdot 100\% \tag{7}$$

where:

$U_{0(1)}$ – the effective value of the voltage of the zero sequence of the fundamental frequency,

$U_{H.\Phi.}$ – rated value of phase voltage;

$U_{0(1)}$ determined by the formula:

$$U_{0(1)} = \frac{U_{A(1)}Y_A + U_{B(1)}Y_B + U_{C(1)}Y_C}{Y_A + Y_B + Y_C + Y_0} \tag{8}$$

where:

Y_A, Y_B, Y_C, Y_0 – phase conductivity A, B, C and zero wire;

✦ frequency deviation:

$$\Delta f = f - f_H \tag{9}$$

where:

f – current frequency value,

f_H – frequency rating (Rey and Muneta 2011).

The applied mathematical apparatus is an effective tool for analyzing and selecting power supply systems for space rocket complexes, with provision for control and quality management of electric power. It enables the modeling of various operational scenarios, assessment of power quality indicators, and optimization of system parameters to ensure stability and reliability. By utilizing advanced computational methods, the approach allows for the identification of potential risks, inefficiencies, and areas for improvement in power distribution and backup strategies. Mathematical modeling supports the development of adaptive control algorithms that enhance fault tolerance and energy efficiency. As a result, the integration of this methodology ensures a high-performance power supply system capable of meeting the stringent requirements of space rocket infrastructure.

2.3. Results of the research and discussion

Electricity quality standards (EN 50160:2022; IEEE 1547:2003), along with the obtained results of electricity quality (EQ) values recorded during the development and execution of the PSS SRC Cyclon-4 experiment, are presented in Table 1. These results provide a comprehensive assessment of the power supply system's performance under different operating conditions. During the analysis, two distinct types of norms were established: normally permissible and maximum permissible values. The normally permissible values define the acceptable range within which the system operates efficiently without affecting performance. In contrast, the maximum permissible value represents the critical thresholds beyond which power quality deviations could lead to potential system failures or malfunctions. Comparing experimental data with these standardized norms enables the identification of inconsistencies and areas that require

Table 1. Electricity quality standards

Tabela 1. Normy jakości energii elektrycznej

N	Electricity properties	Electricity quality index units meas	Power quality standards		Maximum obtained values for SRC Cyclone-4
			normally scceptable	maximum permissible	
1.	Voltage deviation	Steady voltage deviation δU_y [%]	5	10	4.1
2.	Voltage non-sinusoidality	Sinusoidal voltage distortion coefficient k_y [%] ✦ for 0,38 kV; ✦ for 6kV, 10 kV	 8.0 5.0	 12.0 8.0	 3.5 1.9
3.	Voltage imbalance	Negative sequence coefficient k_{2U} [%]	2.0	4.0	1.7
		Zero sequence asymmetry coefficient k_{0U}	2.0	4.0	0.8
4.	Frequency deviation	Frequency deviation, hz	0.2	0.4	0.01
5.	Voltage dip	Voltage dip duration Δt_n, C		30	–

optimization. This structured approach ensures that the power supply system meets stringent requirements for stability.

Electricity quality is analysed within the block diagram of the complex PSS algorithm (Fig. 4), which outlines the key processes involved in power supply management. The block diagram visually represents the relationships between various components responsible for monitoring

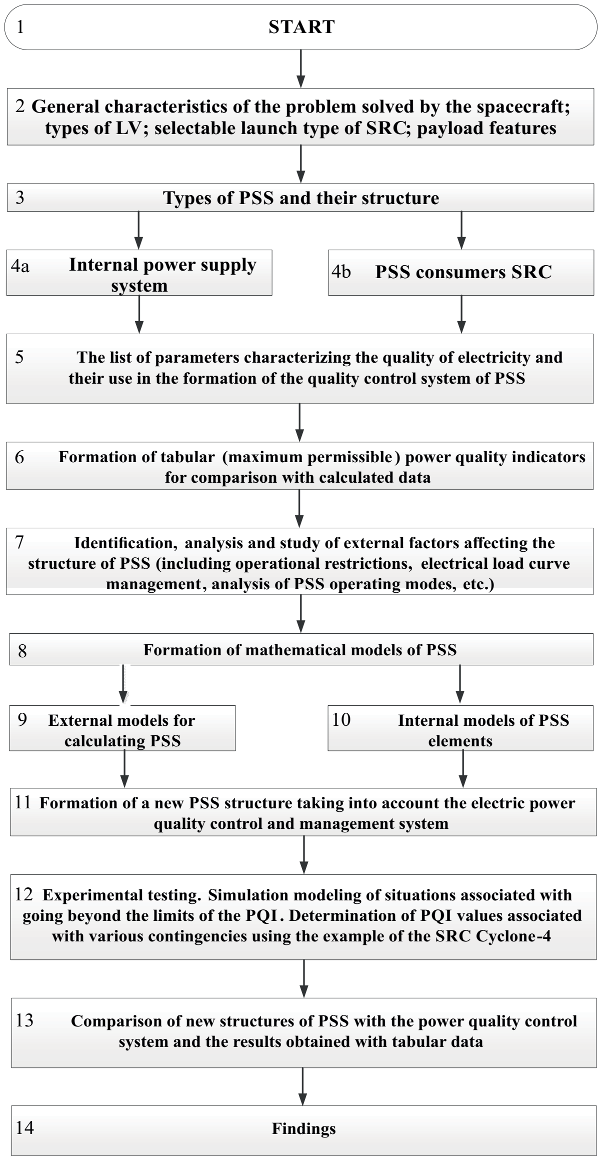

Fig. 4. Block diagram of the algorithm and the new structure of PSS SRC considering the quality of electricity

Rys. 4. Schemat blokowy algorytmu i nowa struktura PSS SRC uwzględniająca jakość energii elektrycznej and controlling power quality parameters. A detailed description of each block and its function is provided in Table 2, offering a structured overview of the system's operation. This analysis helps identify potential inefficiencies and areas for improvement in maintaining a stable and high-quality electricity supply. By integrating these insights, the proposed algorithm enhances the overall performance and reliability of the power supply system.

Analysing the components of the power units, it was found that the main consumers on space rocket complexes are consumers of temperature control systems, production and supply of compressed gases, neutralization systems and units, automated preparation and launch systems (Stones and Collinson 2001; Janik et al. 2017; Fedoreiko 2024).

Figure 5 shows an example load profiles during work at the TC SRC "Cyclone 4M". The cyclogram shows 15 involved systems, each of which has up to a dozen consumers.

The significant variation in consumers with large total capacities and their inherent voltage ratings, combined with the growth of converting equipment, mobile equipment, and switching power supplies, negatively affects power quality.

Figure 6 illustrates the dynamics of load growth in systems that contribute to the energy balance of the launch complex and directly influence electricity quality at the cosmodrome. The graph highlights fluctuations in power consumption over time, reflecting the varying operational demands of different subsystems. These changes in load can lead to variations in voltage stability, frequency regulation, and overall power quality, which must be carefully managed to ensure optimal performance. Understanding these dynamics is essential for optimizing energy distribution and ensuring the reliable operation of critical infrastructure at the launch site.

For example, thermostatic systems (stationary and transport) can have a total power of up to 2 MW, whereas in previously created complexes, this figure was approximately 500 kW. Compressed gas production and supply systems are currently characterized by power consumption of up to 0.9–1 MW compared to 200 kW. The type and characteristics of the space rocket complex and launch vehicle play a key role in the growth of consumer power. In addition to the increase in power consumption, the number of converting equipment, propulsion systems, pulse power supplies, and other similar devices is also increasing, which negatively affects the quality of electricity.

The commercialization of spacecraft launches and payload insurance requires a search for a scientifically based compromise between the expected benefits of using spacecraft and the risk of potential losses in the event of adverse incidents. One of the types of risks associated with operations in the space rocket complex during operational periods is emergencies, which lead to the loss by the space rocket complex of the ability to perform specified functions and requiring, in connection with this, changes in technology (order and scope) or termination of work (Sivathanu Pillai 2022; Zalewski et al. 2023).

An abnormal situation is understood as the state of the PSS components that is not provided for by the regular operation program. An emergency can be categorized into two types: non-dangerous and dangerous.

However, if abnormal situations related to the quality of electric power arise for the SRC, then for the power supply system itself, this is one of the modes of its normal functioning.

Table 2. Description of the flowchart of the PSS structure selection algorithm

Table 2. Opis schematu blokowego algorytmu wyboru struktury PSS

N	Operations content
1.	The main objective of the study is to determine the new structure of power supply systems with monitoring and control of the quality of electricity (implemented through the flowchart of the algorithm).
2.	At the design stage, work is carried out to conduct the appearance of PSS, analysis of existing PSS GC. The general characteristics of the space complex affect the structure of the power supply system. Tasks solved by spacecraft: research, testing, navigation, meteorological, etc. LV types and LV launch types: Depending on the payload and its features, various operations are carried out to prepare it at the ground complex (there is a need for power supply of non-standard and expensive equipment, as well as often using non-standard voltage and frequency ratings).
3.	Determination of the list of consumers powered by PSS GC, load criteria. The value of power consumption, current, frequency, the number of consumers and power feeders, the construction of common power supply structures.
4a, 4b.	Study of the organization of building the internal power supply system, based on the requirements (high-voltage cells, circuit breakers, transformers, etc.), as well as power supply systems for consumers and devices of the complex (distribution boards, input distribution devices, guaranteed power boards, etc.). PSS interaction with other systems of the complex.
5, 6.	Determination of the parameters characterizing the indicators of the quality of electric power (PQI), the formation of tables with normal and maximum permissible values of the PQI (section 3).
7.	Determination, analysis and study of external factors affecting the structure of PSS (section 4).
8, 9, 10.	Construction of mathematical models (MM) and calculation of SES characteristics. Internal MM – for the optimal selection of elements and components of power supply: ✦ autonomous power sources (APS), ✦ energy storage devices (ESD), ✦ converting equipment (transformers), etc.; External MM – for calculating power supply systems: ✦ indicators of the quality of electricity, ✦ electrical loads of the complexes, ✦ system reliability, etc. The final model should ensure the achievement of the research goal.
11.	The formation of a new structure of the power supply system, taking into account the development of emergency situations associated with the parameters of the power supply system, and additional elements calculated using mathematical models. Description of requirements, basic characteristics and principle of operation of the power quality control system.
12.	Experimental testing. Description of the principles of simulation modeling of the power supply system of situations associated with going beyond the limits of the control panel. Determination of PQI values associated with various emergency situations using the developed PSS structure as an example with the components of an electric power quality control system for Cyclone-4.
13.	An analysis of the results. The data obtained during the experiment and the tabular (maximum permissible values of the PQI) data are compared. With acceptable indicators of electricity parameters (if the indicators are within the normal range), the selected structure of the power supply system with management and an electric power quality control system is correct.

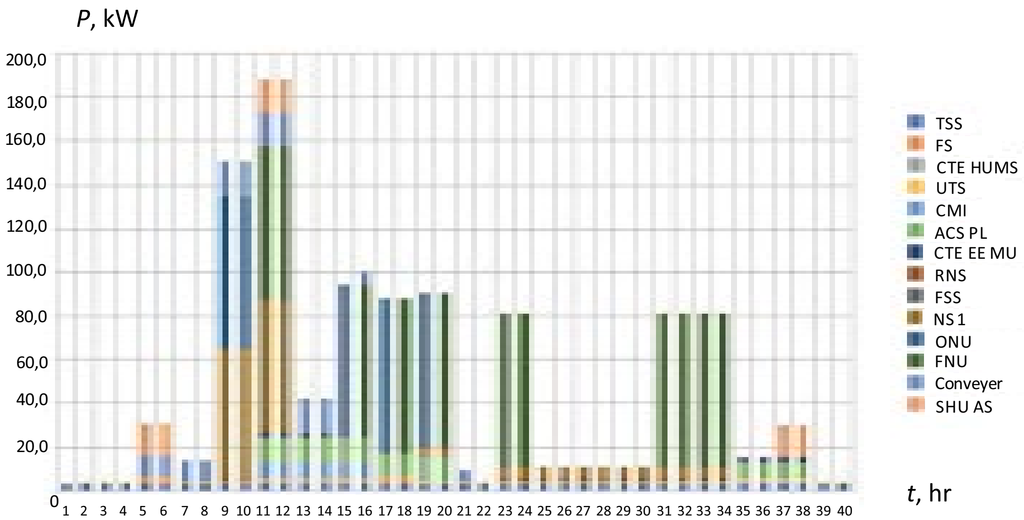

Fig. 5. Graph of electrical loads during work at the TC “Cyclone 4M”

Rys. 5. Wykres obciążeń elektrycznych podczas pracy w TC „Cyclone 4M”

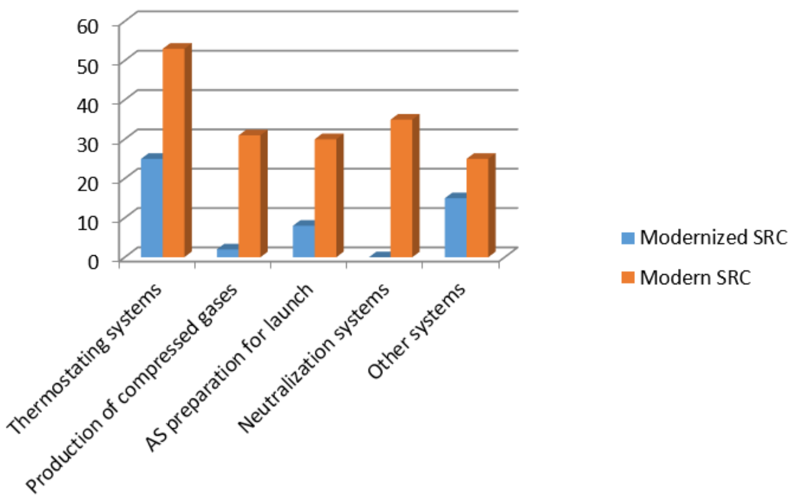

Fig. 6. Percentage ratio of loads that affect to the power quality

Rys. 6. Procentowy udział obciążeń wpływających na jakość energii elektrycznej

It should be noted that some situations that are abnormal for the PSS to the SRC can become emergencies, and their consequence will be the abolition of prelaunch preparation.

The general list of emergencies in the SES is given in Table 3 (Flores 2002; Lamoree et al. 1994; Bollen 1996; Pazynich et al. 2024).

Table 3. The list of emergency situations associated with PQ

Tabela 3. Lista sytuacji awaryjnych związanych z PQ

Emergency situations	Possible causes of an emergency	Consequence and Parry Methods
Increased voltage High voltage impulses	The electric network receives quite a bit of load from other consumers of the power system, insufficiently efficient operation of the regulation system, shutdown of powerful consumers of thermostatic control systems and ground support equipment KV. The mutual influence of nearby electrical appliances. Incorrect connection of the neutral conductor. Turning on and off powerful consumers, putting into operation part of the power system after an accident.	Emergency shutdown of equipment with data loss in computers. Failure of sensitive equipment. Entering the network of filter elements.
Harmonic voltage distortion Unstable frequency	A significant share of the network load is made up of non-linear consumers equipped with switching power supplies. Incorrectly designed electrical network, working with non-linear loads. Strong overload of the power system. Loss of control of GC systems and launch vehicle preparation.	Sensitive equipment interference. Transformer overheating. Incorrect operation of electrical equipment. Using double voltage conversion.
Undervoltage, voltage dips	Overloaded electrical network, unstable operation of the network voltage regulation system. Inability to use any consumers and NK systems. The tripping of circuit breakers during overloads, the unauthorized actions of the power plant, accidents on power lines.	Overloading power supplies of electronic devices and reducing their resource. Shutdown of equipment at insufficient voltage for its operation. Failure of electric motors. Loss of data in computers. Entering a new power source.

In addition to the technical requirements that are defined in the TT, external factors influence the creation of the structure and operation of the PSS (Fig. 7). The number of components of PSS, converting, switching and protective equipment, UPS power, the number of assembly units, etc. directly depend on the number of SRC zones (structure), technical complexes, their remoteness from each other, consumed power and consumer supply category, voltage range and technology of work on the SRC (Nikolsky et al. 2022a; Pivniak et al. 2022).

Based on the flowchart of the algorithm for the SRC Cyclone-4 (and later for the SRC Cyclone-4M), a new structure of the power supply system was created, including an electric power quality control system. Experimental studies of the system (including PQI) were conducted, with the results partially presented in Table 1 (Pivnyak et al. 2015; Nikolsky et al. 2022b). A diagram of the new structure of the power supply system at the SRC, considering the power quality control system (part of it), is presented in Figure 8 (Pivnyak et al. 2017; Beshta et al. 2015).

As a result of confirming the selected model, an example of a mnemonic diagram of the power supply system operator is presented, in which the places of control of the power quality parameters of consumers responsible for the preparation and launch of launch vehicles with spacecraft are highlighted in color (Fig. 9).

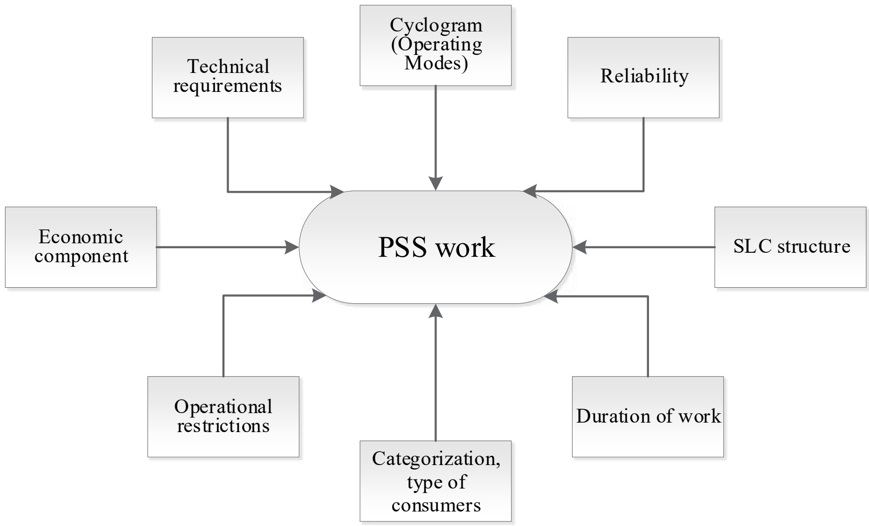

Fig. 7. Factors affecting the power supply structure

Rys. 7. Czynniki wpływające na strukturę zasilania

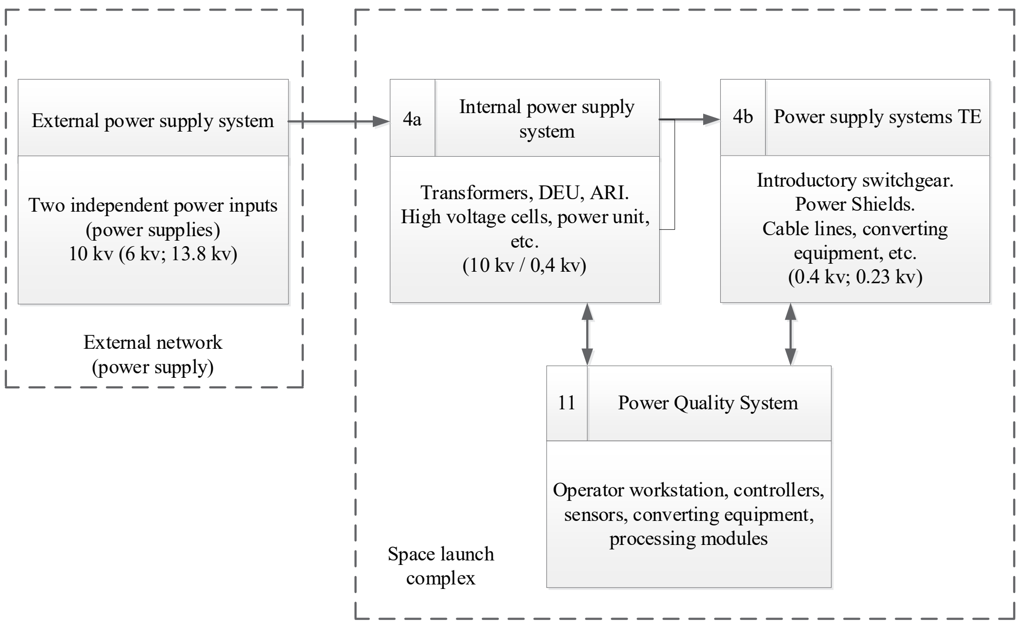

Fig. 8. Scheme of the interaction of power supply systems on the SRC into account the structure of the power quality control system (approximate composition)

Rys. 8. Schemat interakcji systemów zasilania w SRC z uwzględnieniem struktury systemu kontroli jakości energii elektrycznej (przybliżony skład)

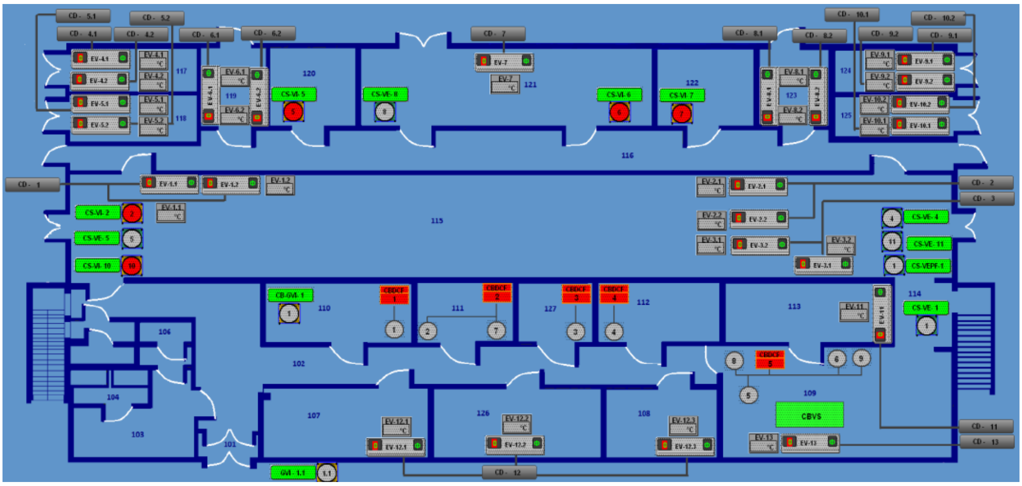

Fig. 9. Mnemonic diagram of the PSS operator (example)

Rys. 9. Schemat mnemoniczny operatora PSS (przykład)

The commercialization of spacecraft launches and payload insurance necessitates a balanced approach between maximizing the expected benefits of spacecraft operations and mitigating the risks of potential losses in the event of adverse incidents. One key risk, emergencies in the space rocket complex, may disrupt operations and require changes in technology or even halt work. Abnormal situations in the power supply system (PSS) may not necessarily pose a threat to the SRC. However, they could indicate the need for corrective actions, particularly when related to electric power quality. Some abnormal conditions, if left unchecked, can escalate into emergencies, leading to disruptions in prelaunch preparation and equipment failures. To address these risks, a new power supply system structure for the SRC has been developed, incorporating a power quality control system, with experimental results demonstrating its effectiveness in improving system stability and reliability.

Conclusions

The analysis of electricity quality standards and experimental data from the PSS SRC Cyclon-4 experiment underscores the critical need for monitoring and controlling power quality. The results shown in Table 1 illustrate the system's performance under varying conditions, comparing normal and maximum permissible values. This comparison enables the identification of potential issues and areas for optimization, ultimately improving system performance and reliability. By adhering to established standards, the stability of the power supply system is ensured, which is vital for preventing failures and malfunctions, thereby maintaining the high quality of electricity delivery.

The integration of electricity quality analysis into the PSS design process, as depicted in the block diagram (Fig. 4), emphasizes the importance of structured and efficient power supply management. The algorithm facilitates a deeper understanding of how various components interact, ensuring that power quality parameters are consistently monitored and controlled. This approach enhances the system's efficiency and optimizes its reliability, which is crucial in complex environments like space rocket complexes. Mathematical models and simulation testing play a crucial role in creating a robust system that can meet demanding operational requirements.

Statistical analysis of the coefficients revealed no asymmetry in the power supply system. The value of the negative sequence asymmetry coefficient, K2U, was 1.7% during the time interval, and the value of the zero sequence coefficient, K0U, was 0.8%, which is considered permissible according to regulatory documents. The average frequency deviation was 0.01 Hz. Moreover, the voltage deviation was within 7%. Additionally, by creating power supply systems, following the algorithm described in the work, energy efficiency can increase by up to 15%.

Addressing potential risks in space rocket complex operations, particularly those related to power supply and electricity quality, is crucial for ensuring smooth operations. The study highlights how abnormal conditions in the power supply system can escalate into emergencies, disrupting prelaunch preparations or even causing equipment failures. The newly developed power supply system structure, which incorporates a power quality control system, aims to mitigate these risks by enhancing system stability and providing more reliable performance. Through experimental studies and continuous analysis of power quality indices, this improved design demonstrates its effectiveness in managing emergencies and optimizing overall system resilience.

It is also worth pointing out a further potential research direction, taking into account the impact of RES, the further use of intelligent systems for energy management and control, including AI and simulation, to realise further improvements. This type of research could focus on the development of new optimisation algorithms to better integrate RES into power grids, as well as the application of AI to forecast and manage the variability of production from renewable sources. Furthermore, the development of self-learning systems can contribute to the automation of energy management processes, thereby increasing the efficiency and reliability of entire energy systems.

Key findings include:

1. The techniques for designing and analyzing electrical loads and operating modes of power supply systems are outdated and do not meet modern requirements. To ensure energy efficiency in PSS operation with modern loads, comprehensive criteria for the quality and reliability of power supply to SRC consumers must be developed.

2. The task is defined: creating and applying new, practical methods and integrated methodological approaches for designing uninterrupted and reliable power supply systems for the SRC.

3. An analysis of regulatory documents identifies 11 fundamental indicators that characterize the quality of electric energy, with Corresponding Table values indicating acceptable and maximum permissible limits. This analysis also addresses potential contingencies in SRC power supply systems.

4. The categories of power receivers at the SRC are identified, highlighting the specific features of the power supply.

5. The algorithm presented in Figure 2 has been developed for the Cyclone-4 power supply system. A power quality control system has been developed, and experimental testing has been conducted, with partial results presented in Table 1.

6. The development of power supply systems for next-generation space rocket complexes using the above algorithm will allow to increase the energy efficiency of power supply systems, the reliability and reliability of the PSS operation, reduce the level of electricity losses in the network, prevent and parry emergencies in the PSS that arise in all modes of operation of the SRC, improve the stability of the power supply systems and increase the period of operation of electrical equipment.

This work was conducted within the projects "Development, manufacturing and testing of power supply systems for the SRC 'Cyclone -4' (Brazil), and power supply systems for the SRC 'Cyclone -4M' (Canada)".

The Authors have no conflicts of interest to declare.

References

Bennett et al. 2001 – Bennett, E.B., Mingst, A., Simon, S. and Graedel, T.E. 2001. Improving the overall environmental performance of existing power generating facilities. *IEEE Transactions on Energy Conversion* 16(3), pp. 234–238, DOI: 10.1109/60.937202.

Beshta et al. 2015 – Beshta, O., Albu, A., Balakhontsev, A. and Fedoreyko, V. 2015. Universal model of the galvanic battery as a tool for calculations of electric vehicles. *Power Engineering, Control and Information Technologies in Geotechnical Systems*, pp. 7–11, DOI: 10.1201/b18475-2.

Białobrzeski et al. 2024 – Białobrzeski, O.V., Oliinichenko, M.Iu., Vorona, V.V. and Yakymets, S.M. 2024. Research on the distribution of symmetrical components in an electrical system with a diesel generator set under asymmetrical load. *Electrical Engineering and Power Engineering* 3, pp. 45–54, DOI: 10.15588/1607-6761-2024-3-5.

Bollen, M. 1996. Voltage Sags: Effects, Prediction and Mitigation. *Power Engineering Journal*, pp. 129–135.

Das et al. 2024 – Das, O., Zafar, M.H., Sanfilippo, F., Rudra, S. and Kolhe. M.L. 2024. Advancements in digital twin technology and machine learning for energy systems: A comprehensive review of applications in smart grids, renewable energy, and electric vehicle optimisation. *Energy Conversion and Management: X*, 24, DOI: 10.1016/j.ecmx.2024.100715.

Dudek, M. 2014. The model for the calculation of the dispersed iron ore resource purchase cost in the world class manufacturing (WCM) logistics pillar context. *Metalurgija* 53(4), pp. 567–570.

Dugan, R.C. 2004. Electrical Power Systems Quality. *Digital Engineering Library*, 521 p.

Dychkovskyi et al. 2019 – Dychkovskyi, R., Tabachenko, M., Zhadiaieva, K. and Cabana, E. 2019. Some aspects of modern vision for geoenergy usage. *E3S Web of Conferences* 123, DOI: 10.1051/e3sconf/201912301010.

Dychkovskyi et al. 2024 – Dychkovskyi, R., Dyczko, A. and Borojević Šoštarić, S. 2024. Foreword: Physical and Chemical Geotechnologies – Innovations in Mining and Energy. *E3S Web of Conferences* 567, DOI: 10.1051/e3sconf/202456700001.

EN 50160:2022 Voltage characteristics of electricity supplied by public electricity networks.

ESPI 2023. European Space Policy Institute. Strategic Autonomy in the European Space Sector: Challenges and Policy Responses. [Online:] https://www.espi.or.at [Accessed: 2025-04-06].

Fedoreiko, V. 2024. Distributed energy generation based on jet-vortex bioheat generators. *E3S Web of Conferences* 567, DOI: 10.1051/e3sconf/202456701001.

Fedoreiko et al. 2013 – Fedoreiko, V.S., Rutylo, M.I. and Iskerskyi, I.S. 2013. Improvement of energy performance of the electrotechnological complex for production of solid biofuels using neural controller. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* 5, pp. 78–85.

Fedoreiko et al. 2014 – Fedoreiko, V.S., Rutylo, M.I., Lutsyk, I.B. and Zahorodnii, R.I. 2014. Thermoelectric modules application in heat generator coherent systems. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* 6, pp. 111–116.

Flores, R.A. 2002 State of the art in the classification of power quality events, an overview. Proceedings of the 2002 *10th International Conference on Harmonics and Quality of Power*, pp. 17–20, DOI: 10.1109/ICHQP.2002.1221398.

Frolov, V.P. 2010. The method of forming the structures of uninterrupted power supply systems of launch complexes based on modeling: Ph.D. dissertation in technical sciences: 05.07.06. National Aerospace University named after N.E. Zhukovsky "Kharkiv Aviation Institute", 176 p.

Gladky, E.G. and Perlik, V.I. 2000. Influence of safety factors, used on designing, upon launch vehicles flight safety indexes. *50th International Astronautical Congress*, IAF. Rio-de-Janero, 119 p.

Golovchenko et al. 2020 – Golovchenko, A., Dychkovskyi, R., Pazynich, Y., Edgar, C.C., Howaniec, N., Jura, B. and Smolinski, A. 2020. Some Aspects of the Control for the Radial Distribution of Burden Material and Gas Flow in the Blast Furnace. *Energies* 13(4), DOI: 10.3390/en13040923.

Hajji et al. 2020 – Hajji, M.E, Mahmoudi, H. and Labbadi, M. 2020. The electromagnetic interferance caused by high voltage power lines along the electrical rail-way equipment. *International Journal of Electrical and Computer Engineering* 10(5), pp. 4581–4891, DOI: 10.11591/ijece.v10i5.pp4581-4591.

Hladkyi, E.H. 2020. New approaches to comprehensive assessment of flight safety and reliability of rocket and space systems: dissertation of Doc. of Tech. Sc.: 05.07.02 (*Novi pidkhody do kompleksnoho otsiniuvannia polotnoi bezpeky i nadiinosti raketnokosmichnykh system: dys. dok. tekhn. nauk: 05.07.02*). Dnipro, 370 p. (*in Ukrainian*).

IEEE 1547:2003-Standard for Interconecting Distributed Resources with Electric Power System.

Janik et al. 2017 – Janik, P., Kosobudzki, G. and Schwarz, H. 2017. Influence of increasing numbers of RE-inverters on the power quality in the distribution grids: A PQ case study of a representative wind turbine and photovoltaic system. *Frontiers in Energy* 11(2), pp. 155–167, DOI: 10.1007/s11708-017-0469-3.

Kannu, P.D. and Thomas, T.M. 2003. Lightning-induced voltages in a satellite launch-pad protection system. *IEEE Transactions on Electromagnetic Compatibility* 45(4), pp. 644–651, DOI: 10.1109/TEMC.2003.819064.

Kosenko et al. 2024 – Kosenko, A., Khomenko, O., Kononenko, M., Myronova, I. and Pazynich, Y. 2024. Raises advance using borehole hydraulic technology. *E3S Web of Conferences* 567, DOI: 10.1051/e3sconf/202456701008.

Kumawat et al. 2023 – Kumawat, H., Tundwal, P. and Dave, V. 2023. Artificial Intelligence-Enabled Fault Detection and Diagnosis for Improved Power Quality in Hybrid Renewable Energy Systems. *3rd International Conference on Advancement in Electronics and Communication Engineering*, pp. 480–485, DOI: 10.1109/AECE59614.2023.10428200.

Kuznietsov, E.I. 2024. Thirty Years in Orbit. Second Edition. To the 32nd Anniversary of the Establishment of the State Space Agency of Ukraine (*Trydtsiat rokiv na orbiti. Druhe vydannia. Do 32-richnytsi utvorennia Derzhavnoho kosmichnoho ahentstva Ukrainy*). Kyiv: Space-Inform, 124 p. (*in Ukrainian*).

Lamoree et al. 1994 – Lamoree J., Mueller D., Vinett P., Jones W. and Samotyj, M. 1994. Voltage Sag Analysis Case Studies. *IEEE Transactions on Industry Applications* 30(4), pp. 1083–1089, DOI: 10.1109/28.297926.

Linnik, A.K. 2021. The systematic approach to the design of rocket and space technology: an illustrated course of lectures in a nutshell (*Systemnyi pidkhid do proektuvannya raketno-kosmichnoi tekhniky: illustrovannyi kurs lekcii styslo*). Dnipro: LIRA, 80 p. (*in Ukrainian*).

Lofstrom, K.H. 1985. The Launch Loop – A low-cost earth-to-high-orbit launch system. *21st Joint Propulsion Conference*, Monterey, CA, USA, DOI: 10.2514/6.1985-1368.

Mahmood et al. 2024 – Mahmood, M., Chowdhury, P., Yeassin, R., Hasan, M., Ahmad, T. and Chowdhury, N.-U.-R. 2024. Impacts of digitalization on smart grids, renewable energy, and demand response: An updated review of current applications. *Energy Conversion and Management: X* 24, DOI: 10.1016/j.ecmx.2024.100790.

Misljenovic et al. 2023 – Misljenovic, N., Znidarec, M., Knezevic, G., Sljivac, D. and Sumper, A. 2023. A Review of Energy Management Systems and Organizational Structures of Prosumers. *Energies* 16(7), DOI: 10.3390/en16073179.

Nikolsky et al. 2020 – Nikolsky, V., Kuzyayev, I., Dychkovskyi, R., Alieksandrov, O., Yaris, V., Ptitsyn, S., Tikhaya, L., Howaniec, N., Bak, A., Siudyga, T., Jura, B., Cabana, E., Szymanek, A. and Smoliński, A. 2020. A Study of Heat Exchange Processes within the Channels of Disk Pulse Devices. *Energies* 13(13), DOI: 10.3390/en13133492.

Nikolsky et al. 2022a – Nikolsky, V., Dychkovskyi, R., Cabana, E. C., Howaniec, N., Jura, B., Widera, K. and Smoliński, A. 2022a. The Hydrodynamics of Translational-Rotational Motion of Incompressible Gas Flow within the Working Space of a Vortex Heat Generator. *Energies* 15(4), DOI: 10.3390/en15041431.

Nikolsky et al. 2022b – Nikolsky, V., Dychkovskyi, R., Lobodenko, A., Ivanova, H., Cabana, E.C. and Shavarskyi, Ja. 2022b. The thermodynamics of the developing contact heating of a process liquid. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* 2, pp. 48–53, DOI: 10.33271/nvngu/2022-2/048.

Papaika et al. 2025 – Papaika, Yu., Pivnyak, G. and Malyshko, M. 2025. Characteristics of Resonance Phenomena at Solar Power Plant Grid Connection Points. *Physical and Chemical Geotechnologies* 9(1), DOI: 10.15407/pcgt.25.01.

Pazynich et al. 2024 – Pazynich, Y., Kolb, A., Korcyl, A., Buketov, V. and Petinova, O. 2024. Mathematical model and characteristics of dynamic modes for managing the asynchronous motors at voltage asymmetry. *Polityka Energetyczna – Energy Policy Journal* 27(4), pp. 39–58, DOI: 10.33223/epj/191779.

Pivniak et al. 2022 – Pivniak, H., Aziukovskyi, O., Papaika, Yu., Lutsenko, I. and Neuberger, N. 2022. Problems of development of innovative power supply systems of Ukraine in the context of European integration. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* 5, pp. 89–103, DOI: 10.33271/nvngu/2022-5/089.

Pivnyak et al. 2015 – Pivnyak, G., Rogoza, M., Papaika, Y. and Lysenko, A. 2015. Traction and energy characteristics of no-contact electric mining loc omotives with AC current thyristor converters. *Power Engineering, Control and Information Technologies in Geotechnical Systems*, 1–6, DOI: 10.1201/b18475-1.

Pivnyak et al. 2021 – Pivnyak, G, Azukovskiy, O., Papaika, Yu., Careres Cabana, E., Olczak, P. and Dyczko, A. 2021. Assessment of power supply energy efficiency by voltage quality criterion. *Rynek Energii* 4(155), pp. 75–84.

Pivnyak et al. 2024 – Pivnyak, G., Azukovskiy, O., Papaika, Y., Caseres Cabana, E., Miedziński, B., Polnik, B., Jamróż, A. and Polyanska, A. 2024. Managing the power supply energy efficiency by means of higher harmonics. *Polityka Energetyczna – Energy Policy Journal* 27(4), pp. 59–80, DOI: 10.33223/epj/191813.

Pivnyak et al. 2017 – Pivnyak, G.G., Zhezhelenko, I.V., Papaika, Yu.A. and Lysenko, O.H. 2017. Interharmonics in power supply systems. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* 6, pp. 109–114.

POLSA 2020. Polish Space Strategy 2017–2030. Polish Space Agency. [Online:] https://polsa.gov.pl [Accessed: 2025-04-15].

Polyanska et al. 2024a – Polyanska, A., Pazynich, Y., Mykhailyshyn, K., Babets, D. and Toś, P. 2024a. Aspects of energy efficiency management for rational energy resource utilization. *Rudarsko-Geološko-Naftni Zbornik* 39(3), pp. 13–26, DOI: 10.17794/rgn.2024.3.2.

Polyanska et al. 2024b – Polyanska, A., Pazynich, Y., Petinova, O., Nesterova, O., Mykytiuk, N. and Bodnar, G. 2024b. Formation of a Culture of Frugal Energy Consumption in the Context of Social Security. *ICON: Journal of the International Committee for the History of Technology* 29(2), pp. 60–87, DOI: 10.11590/icon.2024.2.03.

Reva et al. 2025 – Reva, V., Zemlyanyi, K., Udovyk., O., Leonov, O. and Jamiński, M. 2025. Power Supply Systems for Space Rocket Complexes: Considerations for Power Quality Management and Control. *Physical and Chemical Geotechnologies* 9(1), DOI: 10.15407/pcgt.25.12.

Rey, G.R. and Muneta, L.M. 2011. Power Quality Harmonics Analysis and Real Measurements. Data InTech, 289 p.

Richert et al. 2024 – Richert, M., Dudek, M. and Sala, D. 2024. Surface Quality as a Factor Affecting the Functionality of Products Manufactured with Metal and 3D Printing Technologies. *Materials* 17(21), DOI: 10.3390/ma17215371.

Sandhu, S.K. and Jain, K. 1999. Operational Aspects of Self-Excited Induction Generator Using a New Model. *Electric Machines & Power Systems* 27(2), pp. 169–180, DOI: 10.1080/073135699269370.

Seheda et al. 2024 – Seheda, M.S., Beshta, O.S., Gogolyuk, P.F., Blyznak, Yu.V., Dychkovskyi, R.D. and Smoliński, A. 2024. Mathematical model for the management of the wave processes in three-winding transformers with consideration of the main magnetic flux in mining industry. *Journal of Sustainable Mining* 23(1), pp. 20–39, DOI: 10.46873/2300-3960.1402.

Sivathanu Pillai, A. 2022. Rocket Systems Development. [In:] *Introduction to Rocket Science and Space Exploration*, pp. 81–114, Boca Raton, DOI: 10.1201/9781003323396-5.

Sobolev et al. 2020 – Sobolev, V., Cabana, E.C., Howaniec, N., Dychkovskyi, R., Jura, B., Bąk, A., Iwaszenko, S. and Smoliński, A. 2020. Estimation of Dense Plasma Temperature Formed under Shock Wave Cumulation. *Materials* 13(21), DOI: 10.3390/ma13214923.

Stones, J. and Collinson, A. 2001. Power Quality. *Power Engineering Journal* 15(2), pp. 58–64, DOI: 10.1049/pe:20010201.

Tabachenko et al. 2016 – Tabachenko, M., Saik, P., Lozynskyi, V., Falshtynskyi, V. and Dychkovskyi, R. 2016. Features of setting up a complex, combined and zero-waste gasifier plant. *Mining of Mineral Deposits* 10(3), pp. 37–45, DOI: 10.15407/mining10.03.037.

Wachowicz, M. 2022. Poland's growing role in the European space sector. *Space Policy* 61, DOI: 10.1016/j.spacepol.2022.101481.

Wessler, L.E. 1986. Supervision and Monitoring Systems for Communications Power Plants from Remote Locations. *INTELEC '86 – International Telecommunications Energy Conference*, pp. 259–268, DOI: 10.1109/intlec.1986.4794435.

Zalewski et al. 2023 – Zalewski, P., Kachel, S. and Motyl, K. 2023. Space Rocket for Air-rocket System. *Journal of Konbin* 53(2), pp. 45–64, DOI: 10.5604/01.3001.0053.7125.

Vadym Reva, Kostyantyn Zemlyanyi, Oleksandr Udovyk, Oleksii Leonov,
Maciej Jamiński, Dariusz Sala

Kompleksowe badanie systemów zasilania zespołów rakiet kosmicznych ze szczególnym uwzględnieniem sterowania i zarządzania jakością energii

Streszczenie

Praca poświęcona jest rozwiązaniu problemów i zwiększeniu całkowitej mocy konsumpcyjnej projektowanych kompleksów rakiet kosmicznych (SRC). Wraz ze wzrostem liczby różnorodnych odbiorników energii elektrycznej pojawia się problem kompatybilności elektromagnetycznej oraz jakości energii, co wpływa negatywnie na ekonomikę projektów. Niewystarczająca jakość energii prowadzi do zakłóceń pracy urządzeń oraz zwiększenia strat. W pracy rozważono i opisano różne struktury systemów zasilania kompleksów rakiet kosmicznych, wskazując ich zalety i wady. Przeprowadzono analizę możliwych zdarzeń wpływających na jakość energii w SRC oraz podano główne wskaźniki norm jakości, takie jak wahania napięcia, harmoniczne czy migotanie napięcia. Opracowano schemat blokowy algorytmu i nową strukturę systemu zasilania SRC, uwzględniającą zapewnienie wysokiej jakości energii. Szczegółowo opisano algorytm doboru struktury systemów zasilania, kładąc nacisk na praktyczną implementację. Zwrócono uwagę na czynniki i osobliwości działania systemów zasilania SRC, w tym zmienność obciążenia, wymagania środowiskowe oraz konieczność pracy w trybie awaryjnym. Opracowany algorytm został zastosowany do systemu zasilania kompleksu rakietowego „Cyklon-4”. Na jego podstawie stworzono system kontroli jakości energii elektrycznej umożliwiający monitorowanie parametrów w czasie rzeczywistym i szybką reakcję na odchylenia od norm. W ramach pracy przeprowadzono prace eksperymentalne, a wyniki badań potwierdziły skuteczność zaproponowanego rozwiązania. Głównym celem było wdrożenie algorytmu wyboru nowej struktury systemów zasilania SRC z uwzględnieniem jakości energii elektrycznej, co pozwala na zwiększenie niezawodności, efektywności oraz bezpieczeństwa projektowanych kompleksów.

Słowa kluczowe: systemy zasilania (PSS), kosmiczne kompleksy rakietowe (SRC), energia, wskaźniki jakości energii elektrycznej