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Investigation of the Operation of the Electromechanical System of an Autonomous Photovoltaic Pumping Station

Abstract: The article analyzes the structure and operation of a photovoltaic pumping station. The key components of the system, such as solar panels, electronic controllers, electromechanical pumps, and energy storage, were studied. In particular, various methods of maximising energy output from solar panels and optimising the efficiency of pumping systems were investigated. The results of the study showed that the efficient operation of a photovoltaic pumping station depends on the precise balancing of electromechanical components, optimal use of solar energy, and efficient management of electronic systems. Recommendations for improving the efficiency and reliability of the system have been put forward. In the course of the study, it was established that one of the key factors for the effective operation of a photovoltaic pumping station is the proper selection of solar panel type and the optimisation of their placement to ensure maximum solar energy conversion. The issue of storing surplus energy was also analysed to maintain stable system performance during periods of reduced solar activity. In addition, the research involved modelling and experimental studies of various operating modes of the pumping station, including changes in load and fluctuations in solar radiation. This made it possible to obtain valuable results regarding the dynamic characteristics of the system and its compliance with the specified technical parameters. An important part of the study was the evaluation of the efficiency and economic feasibility of using a photovoltaic pumping station compared to traditional energy sources for water supply. It was demonstrated that in certain cases the use of solar energy may be not only more environmentally friendly, but also economically advantageous. Overall, the results of this work have significant practical value for developing sustainable energy and the broader application of renewable energy sources. The study of an autonomous photovoltaic pumping station contributes to a deeper understanding of the technological, economic, and environmental aspects of such systems. In conclusion, this scientific work provides greater insight into the principles of operation of autonomous photovoltaic pumping systems and can serve as a basis for further research in renewable energy.

Keywords: photovoltaic energy, autonomous pumping station, electromechanical system, solar panels, pumping systems.

Abbreviations:

AES is power supply systems,

PV is autonomous photovoltaic,

RES is renewable energy sources.

Introduction

To irrigate crops, pump water for domestic use, and water livestock, pumping systems with an appropriate power source are needed. However, in rural areas, energy sources may be far from water sources, which increases the cost of building infrastructure (*Kondalkar et al., 2019*; *Razzaq et al., 2019*; *Kupchuk et al., 2023*; *Tsurkan et al., 2022*; *Puyu et al., 2021*). Now there are many sources of electricity based on internal combustion engines that can be used for autonomous water pumping systems. They are portable, easy to install, and independent of infrastructure. However, these systems require maintenance and fuel, and have a negative impact on the environment. The use of renewable energy is an attractive option for autonomous water supply systems in rural and desert areas.

In particular, generating electricity using photovoltaic cells looks very attractive for water supply systems. Photovoltaic systems have many advantages, such as ease of installation, low infrastructure requirements, stability, and quietness. They can be used even in remote locations and require little maintenance.

The use of autonomous photovoltaic water pumping systems should help improve life in remote areas and preserve the environment (*Razzaq et al., 2019*; *Mazur et al., 2021*; *Semenov et al., 2021*; *Semenov et al., 2019b*; *Hraniak et al, 2022*; *Honcharuk et al., 2023*; *Lohosha et al., 2023*).

The purpose of this research work is to create an independent photovoltaic pumping system. The first stage includes the development of the project concept, determination of key control, regulatory and signal parameters. Further development includes the design of the PV power plant as a whole, the selection of appropriate control and regulatory devices and tools that provide control over the work process, and the study of the functioning of the electromechanical system. Automation of a PV power plant will have a positive impact on working conditions, energy and material conservation, and increase production efficiency.

Literature Review

The development of PV pumping stations is grounded in the broader context of renewable energy integration into electromechanical systems. The global shift toward sustainable technologies has intensified research on energy efficiency, system automation, and the reliability of photovoltaic installations for water supply and irrigation in rural or isolated regions. Studies have emphasised the necessity of combining engineering optimisation with environmental and economic considerations to ensure sustainable operation (*Razzaq et al., 2019*; *Puyu et al., 2021*; *Honcharuk et al., 2023*).

A fundamental direction of recent research concerns the optimisation of PV panels and their interaction with electric drive systems. Kondalkar et al. (*2019*) and Kumar et al. (*2021*) analysed the parameters influencing sensor performance and power stability in electromechanical networks, demonstrating that humidity and insulation control significantly affect efficiency. Kupchuk et al. (*2023*) and Tsurkan et al. (*2022*) explored digital processing algorithms and adaptive communication systems, which enable more precise regulation of PV-driven systems under changing environmental conditions. These findings are crucial for ensuring energy independence in autonomous water supply facilities.

Significant attention has been devoted to the automation and modelling of photovoltaic systems. Nazarova (*2020*) and Semenov et al. (*2020*) developed mathematical and computer models for electromechanical devices that incorporate feedback and nonlinear dependencies to simulate transient processes under fluctuating voltage conditions. Similarly, Hrabko et al. (*2024*) investigated frequency-controlled asynchronous drives and diagnostic methods using FPGA systems, which facilitate the detection of failures and enhance operational reliability. These studies collectively demonstrate the essential role of modelling and diagnostics in optimising the performance of photovoltaic pumping stations.

The technical progress in renewable energy systems is also associated with innovations in materials and sensor technologies. Hraniak et al. (*2022*) and Krivoruchko et al. (*2012*) developed models of dielectric and humidity sensors improving the precision of system monitoring. These sensors are integrated into PV systems to measure critical parameters such as temperature, voltage, and current fluctuations, ensuring the stable operation of photovoltaic modules. Additionally, Lohosha et al. (*2023*) highlighted the importance of integrating internal management and marketing mechanisms in renewable energy production systems, underlining the necessity of coordination between technological and organisational components for sustainable functioning.

Further studies address the electromechanical and control aspects of energy conversion. Semenov et al. (*2019a*; *2019b*; *2021*) proposed models of deterministic chaos oscillators and non-standard microwave systems that improve efficiency through the optimisation of self-oscillatory parameters. Such research broadens the theoretical understanding of nonlinear energy systems and provides methodological bases for future photovoltaic applications. Voznyak et al. (*2023*) and Spirin et al. (*2023*) advanced image recognition and analytical algorithms applicable in control and diagnostic systems for renewable energy installations, improving the precision of automated monitoring and predictive maintenance.

The economic and ecological dimensions of renewable technologies are equally important. Mazur et al. (*2021*) and Vasilevskyi et al. (*2023*) demonstrated that digital transformation and precision measurement technologies reduce energy losses and enhance sustainability, particularly in agricultural and rural settings. Studies by Wallin (*2000*) and Gunko et al. (*2021*) complemented this approach with turbulence and airflow models applicable to energy transfer optimisation. Collectively, these contributions form the scientific foundation for designing efficient photovoltaic pumping systems that balance environmental protection with technical feasibility.

Thus, the existing body of research substantiates that the effective operation of photovoltaic pumping stations depends on the accurate modelling of electromechanical parameters, the integration of smart diagnostics, and the sustainable management of energy flows. The combination of advanced materials, digital control systems, and renewable energy technologies creates a coherent interdisciplinary framework supporting the transition toward autonomous, environmentally responsible power systems (*Kupchuk et al., 2023*; *Semenov et al., 2020*; *Hrabko et al., 2024*).

Materials and Methods

Overview of Automated Power Supply Systems

Renewable energy sources are becoming more and more popular in the world, as they allow you to obtain energy without the use of natural fuels and have a minimal negative impact on the environment. Among these sources, solar, wind, hydropower, biofuels and others stand out. One of the areas of their use is automated power supply systems, which provide the necessary energy for various needs, using renewable sources.

Automated energy supply systems are used for residential buildings, as well as for commercial and industrial facilities. One of the main advantages of such systems is their independence from the centralized power supply network. They can operate in remote and inaccessible areas where connection to the general network is impractical or impossible.

The main component of automated systems is the use of solar panels or wind turbines to generate electricity. Solar panels convert solar radiation into electricity through the photovoltaic effect, while wind turbines use the kinetic energy of the wind to generate electricity. These sources can operate in different conditions and provide a constant flow of energy.

For the efficient operation of such systems, it is necessary to use specialized controllers and control algorithms. They allow you to track energy production and consumption, optimize system operation depending on external conditions and user needs.

Such systems have a number of advantages, including reduced energy costs, reduced carbon emissions, increased reliability and resilience to outages from the centralized network. However, they also have their challenges, including a lack of energy at night or in light winds, as well as the need to manage and maintain the system.

The growing interest in automated energy supply systems encourages further research and development in this area. Understanding the principles of their operation and improving control algorithms can contribute to the wider and more efficient use of renewable energy sources, which in turn will help to conserve resources and reduce the negative impact on the environment (*Lohosha et al., 2023*; *Semenov et al., 2019a*; *Semenov et al., 2020*; *Spirin et al., 2023*; *Paziuk et al., 2021*; *Gunko et al., 2021*; *Voznyak et al., 2023*; *Krivoruchko et al., 2012*; *Wallin, 2000*).

For ensure reliable and high-quality power supply to demanding consumers, autonomous (uninterrupted) AES have been used, which include several sources of electricity, such as main, backup and emergency sources. Contributing to this, the possibilities of using RES are coming, since the limited resources of organic fuels and the negative environmental impact of traditional methods of energy production make it relevant.

One of these approaches, the photovoltaic power supply system, includes components that interact with each other to ensure efficient delivery of for electricity from small devices to the overall load. Power supply systems are divided into three categories: grid-connected, stand-alone, and hybrid, including sources such as photovoltaic panels, diesel generators, and wind turbines. Both systems can use storage, such as batteries or supercapacitors, for nighttime or times of insufficient sunlight.

Photovoltaic panels in autonomous systems directly power the load, independent of the utility grid. Stand-alone systems are particularly cost-effective for introducing photovoltaic energy, especially in rural areas with intense solar radiation and limited access to the grid. This can be used for communication systems, water supply, navigation, emergency services, or military facilities that require an additional source of energy.

Stand-alone systems have drawbacks, such as low power storage, batteries with limited capacity, which can lead to the loss of stored energy. Additionally, they have important features such as the need for storage nighttime hours when there is no sunlight, and adjusting the operating power according to the load (*Kupchuk et al., 2023*; *Yaropud et al., 2022*; *Polievoda et al., 2022*; *Vasilevskyi et al., 2023*).

Research and Development of a Block Diagram of an Electric Drive System

Research and development of the structural diagram of the electric drive system is a key aspect in the process of improving electrical engineering systems. This topic focuses on the analysis and determination of optimal components and connections that provide efficient and reliable energy transfer in the system. The research covers the study of various options for structural solutions to meet the needs of the electric drive, and the development includes the creation of conceptual and practical models for implementing the selected structural solutions. An important aspect is ensuring optimal coordination between the various components of the electric drive system to achieve maximum performance and efficiency. As a result of research and development of the structural diagram of the electric drive system, it is possible to improve the quality and reliability of electrical systems in various fields of application, from industry to household devices.

Photopanel is an interface capable of converting light into electrical energy. Modeling this device requires weather data such as irradiance and temperature as input variables. Output parameters can be current, voltage or power. Any change in the input values leads to a change in the results, so it is important to use an adequate model for the photopanel. In this model, the influence of irradiation and temperature on the parameters of the photovoltaic module should be considered. One model is based on using a diode model with series and parallel resistors for more accurate results.

The more accurate the structural model, the more unknown parameters it contains. Often manufacturers' specifications provide insufficient information about parameters that depend on weather conditions. Thus, to establish a mathematical model of a PV panel it is necessary to make assumptions about the physical nature of its behavior (*Figure 1*).

The main goal of the model under study is to achieve maximum power close to the experimental values at any time. The external characteristic of a PV panel I(V) is a nonlinear equation with many parameters that can be classified as design parameters, known constants, and those that need to be calculated. In some cases, simplified methods are used, where some unknown parameters are treated as constants. Such assumptions help reduce the complexity of modeling. However, there are also researchers who consider the values of all internal parameters for more accurate results (*Semenov et al., 2019a*; *Semenov et al., 2020*; *Spirin et al., 2023*; *Paziuk et al., 2021*; *Gunko et al., 2021*).

In general, PV panel is a significant component in renewable energy systems, and developing appropriate models helps to achieve greater efficiency and accuracy in its operation.

Considering the power value calculated above, we will select the AXM144-9-166-470 PV panel with the technical characteristics shown in Table 1 (*See Appendix*).

Two experiments were conducted using this model. Namely, the study of dynamic and static characteristics at the nominal and reduced input voltage of the PV panel. In the following two experiments, the load torque on the pump motor shaft is reduced by 10 Nm per 1 s. The pump in this model is represented by the following equation (21):

$$K=\frac{M_n}{\omega_n^2}=\frac{72}{152.62^2}=0.00292$$

Transients' Processes at Rated Input Voltage

The function scheme diagram of the soft start device is shown in Figure 2 (*See Appendix*).

Having modeled the system, graphs of transient processes were obtained, which clearly show the functioning of the interconnected components of the system. The experiment was carried out at a photopanel output voltage of 490 V (*Tsurkan et al., 2017*; *Hrabko et al., 2024*).

As a result of system modeling at the nominal input voltage transient processes were obtained, which can be seen in Figure 2 and Figure 3 (*See Appendix*). In the first case the voltage during the load-on phase of the motor gradually increases to the nominal value of 380 V. As the load changes on both the rotor and stator, the currents become smaller and approach the motor's rated values, as seen in Figure 2. Looking at Figure 3, it can be observed that the motor reaches the set speed in 1.1 seconds. The torque on the motor shaft also approaches the rated value (*Yaropud et al., 2022*; *Nazarova, 2020*).

Thus, at the nominal input voltage this system demonstrated performance that meets the expected result. This confirms that the system under consideration is able to operate stably and efficiently under rated conditions.

Transients at Input Voltage Reduction

When analyzing the transient processes when the input voltage in the system is reduced interesting dependencies and characteristics were found that can be illustrated by figures and analyzed in detail.

Reducing the input voltage led to a change in the system dynamics. The transient process showed that as the input voltage decreased, the voltage at the supply output began to decrease. In the first moments, a significant voltage drop was observed, indicating that the system reacted to this decrease quite quickly. Then, according to the graph, the output voltage stabilized at a certain value, showing that the system had reached a new state of equilibrium.

Observing the change in the currents in the system, it can be noted that they also decreased in response to the reduced voltage. Initially, there was a short-term current peak, which was due to the system's reaction to the sudden change in conditions. However, later the currents began to decrease and, similarly to the voltage, stabilized at the new value.

Changes in transients also affected the system's efficiency characteristics. It turned out that when the input voltage was reduced, the system efficiency initially decreased slightly. However, later, when the system reached a new state of equilibrium, the efficiency stabilized at a certain level.

The functional diagram of the soft start device is shown in the Figure 4 (*See Appendix*).

Since in real-world conditions, systems that use PV panels can be subject to changes in weather conditions, namely temperature and irradiation, the output voltage can also change. As an example, in the experiment, the output voltage of the PV panel will be reduced by 100 V (*Figure 4*; *Figure 5*).

Having considered the transients obtained as a result of the second experiment it is worth noting that the power decreased due to the lower input voltage. This resulted in changes in currents and torque on the motor shaft.

Discussion

The transient analysis confirms that the reduction of the input voltage has a significant impact on the system operation. The displayed changes in voltage, currents, and efficiency show how the system adapts to the new conditions and ensures stable operation. A detailed analysis of these processes is an important step in improving and optimizing the operation of the electric drive system.

In parallel with the analysis of voltage and current dynamics, it is worth considering the impact of input voltage reduction on other system parameters.

In particular, an important aspect is the change in the speed of the system's response to voltage reduction. From the graphs, you can see that there is a certain delay before the system begins to adapt to new conditions. This can be important in assessing the system's responsiveness to unpredictable changes in power conditions.

In addition, transients can affect the mechanical stability of the system. A decrease in the input voltage can cause a change in the torque and speed of the system, which in turn can affect its stability and performance.

It is also important to note that lowering the input voltage can lead to increased stress on system elements such as the motor. This can affect how long they last, wear and tear, and the overall reliability of the system.

Transient analysis at input voltage reduction can also help identify possible limitations and risks in system operation. For example, if there is a very slow response to voltage changes, this may indicate problems with the reactivity or insufficient power of the system elements.

As a result, the analysis of transients during input voltage reduction provides a lot of important information about the system operation under conditions of changing input parameters. This analysis is key to ensuring the stability, efficiency, and reliability of the drive system under various conditions.

Conclusion

This study considered aspects of creating an autonomous water supply source based on a photovoltaic renewable power source that works in conjunction with an electric drive based on an induction motor with an autonomous inverter. Taking into consideration the experiments and analysis the following conclusions were obtained:

According to the results of a detailed analysis of scientific and technical literature, the efficiency of a PV power station can be significantly improved by using MPPT algorithms to maximize power extraction from a PV panel. This strategy helps to ensure optimal operation of the PV system.

It has been demonstrated that the combination of a PV panel with an electric drive for panel rotation can be characterized by increased power generation. The correct angle of panel rotation helps to maximize irradiation and temperature parameters, which have a key impact on power generation.

Different methods of electric drive control are investigated, and it is found that in the case of interaction of an induction motor with a pump, the most effective is the use of frequency control. This strategy allows to achieve an optimal ratio between the generated energy and the demand.

Modelling of the autonomous water supply system in MATLAB/Simulink confirmed the compliance of the developed system with the specified requirements. The transient graphs indicate the stability and adequacy of the system's operation in real-world conditions.

Thus, the study indicates that the implementation of an autonomous water supply system based on a photovoltaic power source and an induction drive is a promising and effective approach to ensure reliable and sustainable water supply in remote regions.

Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

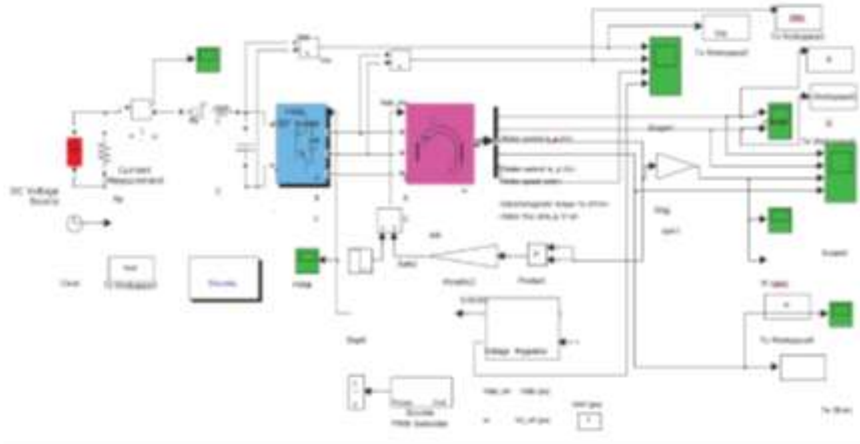

Figure 1. Scheme of the model of the studied system
Source: the author created the material based on (Kupchuk, 2023)

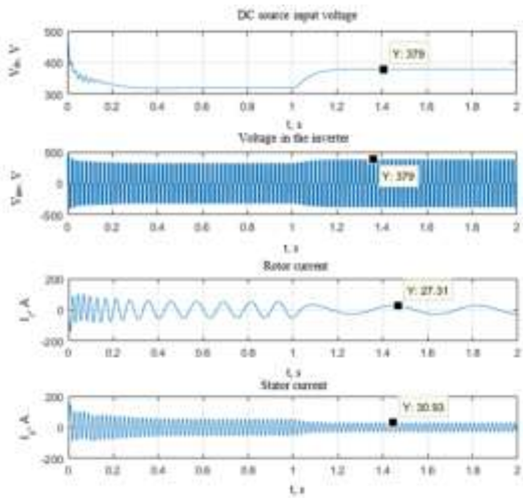

Figure 2. Figure 2. Motor transients at rated input voltage Udc = 490 V
Source: the author created the material based on (*Kupchuk, 2023*)

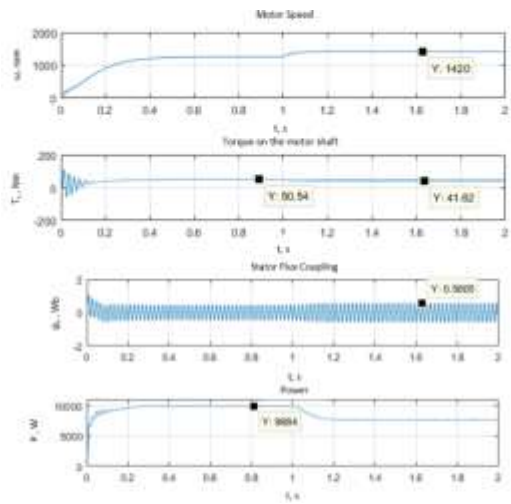

Figure 3. Motor transients at rated input voltage Udc = 490 V
Source: the author created the material based on (Kupchuk, 2023)

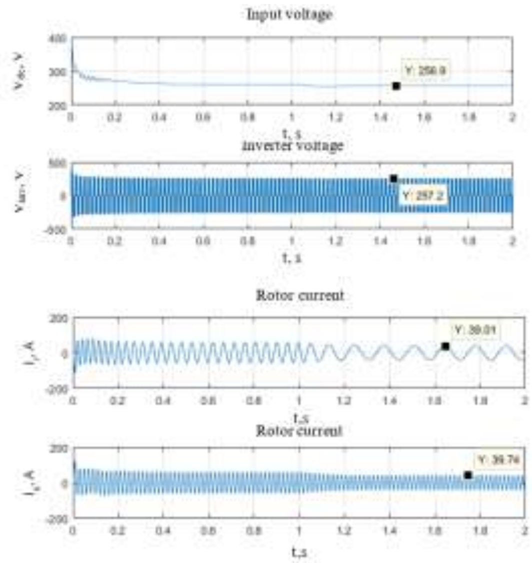

Figure 4. Motor transients at reduced input voltage Udc = 390 V
Source: the author created the material based on (Kupchuk, 2023)

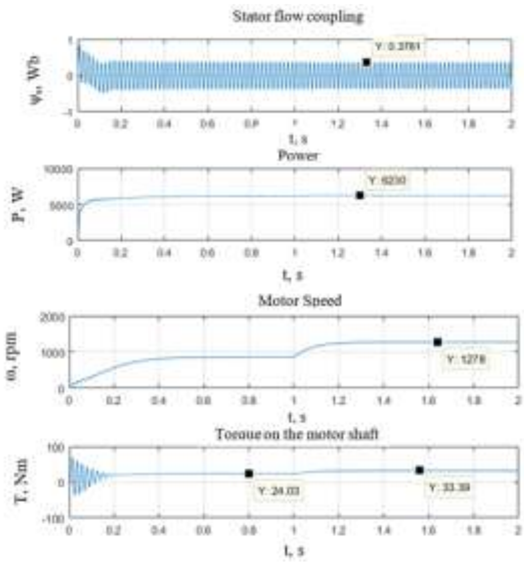

Figure 5. Motor transients at reduced input voltage Udc = 390 V
Source: the author created the material based on (Kupchuk, 2023)

Table 1. Technical characteristics of the AXM144-9-166-470 PV panel

Output power Pmax, W	470
Voltage Pmax Vm, V	41.44
Current Pmax Im, A	10.87
No-load voltage Voc, V	50.16
Short circuit current Isc, A	11.48
Temperature coefficient (Pmax), γ, % / 0C	-0.365
Temperature coefficient (Voc), βvoc, % / 0C	-0.285
Temperature coefficient (Isc), αisc, % / 0C	-0.055
Maximum system voltage Vmax, V	1000
Working temperature, 0C	-40~85

Source: the author compiled the material.