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A METHOD OF LOAD BALANCING BASED ON FUZZY LOGIC IN LOW-VOLTAGE NETWORKS WITH SOLAR PANEL INTEGRATION

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Abstract: This study presents a detailed development and analysis of a photovoltaic system model integrated with a rechargeable battery and equipped with an advanced fuzzy controller based on a DC-DC converter. The key element of the model is an intelligent control system based on the principles of fuzzy logic and implemented using the adaptive neuro-fuzzy inference Systems (ANFIS) toolkit. This approach has made it possible to create a flexible and adaptive management system capable of responding effectively to changing environmental conditions. The model takes into account a wide range of input parameters, including time of day, ambient temperature, and other significant factors affecting the performance of a photovoltaic system. Based on this data, the system predicts the output voltage and optimizes the charging/discharging process of the battery. During the design of the model, the system was thoroughly trained in order to form a knowledge base that includes a set of vague rules and conditions. This made it possible to achieve high modeling accuracy and an adequate reflection of the real behavior of the photovoltaic system. The simulation results demonstrate the effectiveness of the proposed approach and open up new prospects for optimizing the operation of photovoltaic systems, increasing their reliability and reducing operating costs.

Keywords: photovoltaic system, ANFIS, modeling, MATLAB/Simulink, bidirectional converters, rechargeable batteries, generation forecasting, energy consumption optimization, integration of renewable energy sources, distributed microgrids, energy efficiency, stability of power systems, low-voltage networks.

Introduction. In Uzbekistan, the green energy sector is showing rapid development. To date, 16 large solar and wind power plants with a total capacity of 3.5 thousand megawatts have been commissioned, which allows generating up to 10 billion kilowatt-hours of electricity annually. Thanks to these achievements, the share of "green energy" increased to 16% in 2024. This indicates that in a short period of time, the capacity of environmentally friendly energy has increased 2-3 times annually [1].

Such growth rates underline the relevance of the introduction of solar panels as a key tool in the transition to sustainable energy. In addition, the integration of solar panels into low-voltage electric networks opens up new opportunities for optimizing energy distribution, reducing the burden on traditional sources and improving energy efficiency.

The studies [2-9] consider various approaches to the modeling and management of photovoltaic systems aimed at increasing their efficiency and stability. [2] presents a detailed model of a photovoltaic system in MATLAB/Simulink with an emphasis on the integration of bidirectional converters and backup batteries for stable load supply, which is useful for autonomous and hybrid power systems. The study [3] showed that such systems are applicable for integration into domestic and industrial power grids, especially in regions with power supply disruptions. In [4], modified fuzzy neural networks were proposed for predicting solar panel generation, minimizing errors and ensuring a balance between supply and demand. Work [5] demonstrates the use of an energy management system (EMS) based on the MILP method, which reduces energy consumption and increases energy efficiency, especially in smart buildings. In [6], peer-to-peer energy trading in homes with electric vehicles via V2H mode was investigated, which reduces energy costs and is relevant for smart cities. The study [7] suggests a control strategy for three-phase photovoltaic systems that protects inverters from overloads and is useful for microgrids with frequent disruptions. In [8], MPPT algorithms are experimentally compared, where the P&O method achieves an efficiency of more than 97%, which makes it preferable for commercial systems. Work [9] considers the integration of solar and wind generation into the grid with optimal placement of panels and batteries, reducing energy consumption from the grid and increasing electrification in regions with limited infrastructure.

Methodology & empirical analysis. Photovoltaic devices are non-linear devices. Their parameters depend on sunlight and temperature. Sunlight is converted into electricity using photovoltaic cells. Photovoltaic arrays consist of parallel and serial photovoltaic modules. Cells are grouped together to form panels or modules. The voltage and current generated at the terminals of the photovoltaic source can not only supply a DC load, but can also be connected to an inverter to produce alternating current. Photovoltaic cell models have long been used by researchers and professionals to describe the behavior of photovoltaic cells.

The use of renewable energy is extremely important because in many countries, including our country, there are regions far from the main electric networks. Renewable energy can be a solution for energy supply solutions in remote regions, as it does not require the construction of long power transmission lines from power plants to consumers. Similarly, the traditional energy sector, which distributes electricity through power transmission lines, currently has a number of unresolved issues for the smooth functioning of the current energy system [11], [12].

The voltage and current produced by the PV system depend on the light conditions and temperature, as well as on the load to which the system is connected. These parameters determine the efficiency of energy conversion. In practice, the PV matrix output can be used both for direct current supply in autonomous systems and for conversion to alternating current using inverters for connection to electrical networks.

Modeling of a photovoltaic system using the adaptive neural fuzzy inference System (ANFIS) algorithm is the basis for this research paper. The ANFIS algorithm combines the advantages of neural networks and Fuzzy Logic, which makes it possible to effectively model complex systems with nonlinear behavior. This part presents a diagram of the model, reveals the essence of the ANFIS algorithm, and defines further steps for its development.

Database collection.

The fuzzy partitioning of input data is a key step in building the ANFIS system, as it determines how numeric input data is interpreted and processed in terms of fuzzy logic. At this stage, input parameters such as solar radiation and temperature are transformed into linguistic variables (for example, "low", "medium", "high"), each of which has a corresponding membership function. These functions describe the degree to which the input value relates to each of the linguistic terms.

```
clear all
ISCS=8.66;          %% Short circuit current at Panel name plate detalies
IMPS=8.15;          %% Maximum current at from panel name plate detalies
VOCS=37.3;          %% Open circuit voltage from panel name plate detalies
VMPS=30.7;          %% Maximum voltage from panel name plate detalies
alpha=0.086998;     %% Current temperature coeefficient from manufacture
betta=-0.36901;     %% Voltage temperature coeefficient from manufacture
Gs=1000;            %% Sandart Irraniance 1000 W/m2
Ts=25;              %% Sandart tamperature 25 dagrees
for i=1:1000
    Tmin=15;
    Tmax=35;
    T=(Tmax-Tmin)*rand+Tmin; %% Temperature
    Gmin=0;
    Gmax=1000;
    G=(Gmax-Gmin)*rand+Gmin; %% Irradiance
    IMP(i)=IMPS*(G/Gs)*(1+(alpha*(T-Ts)));    %% Maximum current of the given
irrandiance and Temperature
    VMP(i)=VMPS+(betta*(T-Ts));                %% Maximum voltage of the
given irrandiance and Temperature
    PMP(i)=VMP(i)*IMP(i);                     %% Maximum Power of the given
irrandiance and Temperature
    input(i,:)=[G, T];
    output (i,1)=4*VMP(i);
    output1(i,1)=IMP(i);
    output2(i,1)=PMP(i);
    data(i,:)=[G T output(i,1)];
end
```

Fig.1. Database collection

System training.

The system is trained using measurement data. The input data is fed into the system, and the output parameters are adjusted to minimize errors. A hybrid method combining gradient descent and least squares is used for training.

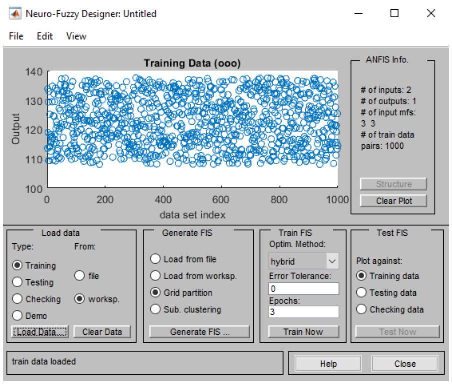

Fig.2. System training

The use of fuzzy logic and a fuzzy controller based on it provides a number of advantages in modeling and further forecasting electrical networks [13], [14]. The program has many tools for managing the system, from which the Anfis Edit tool was selected. The system was trained on the basis of data collected for system modeling. After entering the required algorithm in the form of the code shown in Figure 1, the system was successfully trained in databases for calculations.

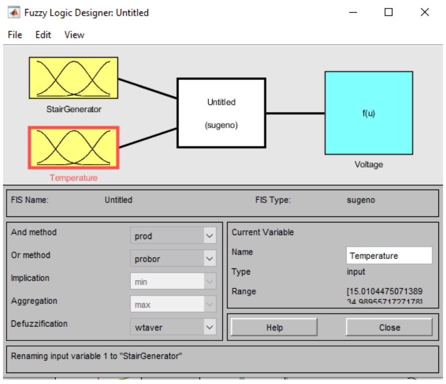

Fig.3. Fuzzy Logic Constructor

The constructor has input parameters: StairGenerator (in this case, time) and Temperature (temperature, membership functions are defined for it, which set the range and level of division into linguistic values). The central unit (Untitled (Sugeno)) is the core of a fuzzy system. This block performs input data processing based on the Sugeno rule base and fuzzy logic method. The output parameter of the system (Voltage), the voltage calculated based on the processing of input data. The key settings used for the fuzzy logic algorithm are shown at the bottom of the image.

Rule generation.

Based on the membership functions, a rule base is created that describes the relationship between inputs and outputs. For example, "If the solar radiation is high and the temperature is low, then the output power is maximum." Elements of fuzzy logic make it possible to clarify and more accurately predict the behavior of the system [15]. In this case, each triangular function is a fuzzy set. The position and shape of the triangle determine the degree to which the value of a variable belongs to this set. With this set of rules and the choice of a triangular function, we get a voltage output signal equal to Voltage=123V at the outputs.

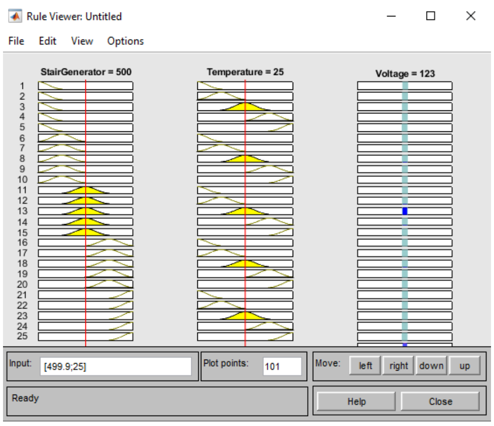

Fig.4. Rule Viewer

Forecasting:

After training, the system is able to predict parameters such as the output power of a photovoltaic panel, taking into account changing conditions.

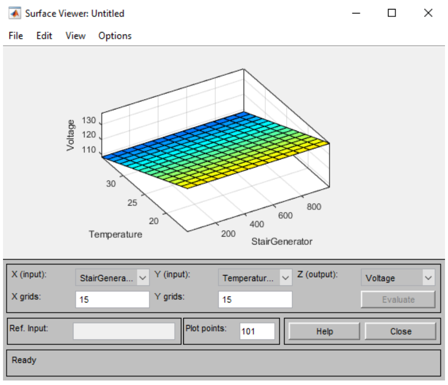

Fig.5. Surface viewer

The presented image demonstrates a three-dimensional graph that visualizes the dependence of the voltage value on two other variables: StairGenerator and Temperature. The graph surface shows how the voltage changes depending on temperature changes and the StairGenerator parameter. The color of the surface reflects the amount of stress at each point.

Using all the necessary modeling steps to develop a photovoltaic system, the model shown in Figure 6 below was created.

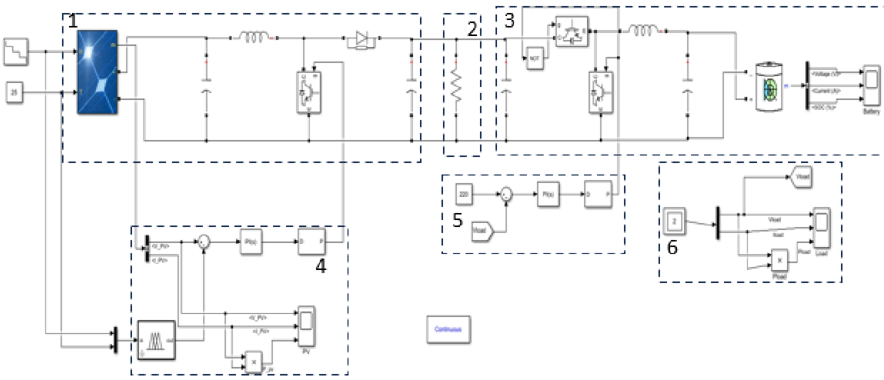

Fig.6. Model of the photovoltaic system

1 - PV system, 2 - load, 3 - battery pack, 4 - PV control unit using Fuzzy controller, 5 – PI contraller battery pack, 6 – visual analysis unit of measuring instruments

The above image shows a structural model of a photovoltaic system modeled in MATLAB/Simulink. The system includes several key components: 1. The photovoltaic module serves as the main source of energy generation. It converts solar radiation into electrical energy. Voltage and current are generated at the output of the solar panel, which depend on the level of solar radiation and temperature. 2. The load is connected to the system output. The allocation of a separate load block allows you to analyze how the generated energy is used to power consumers, as well as load balancing in a low-voltage network.3. The battery pack is integrated into the system to store excess energy generated by the solar panel. The voltage (Voltage), current (Current) and charge level (SOC) of the battery are monitored, which ensures reliable operation of the system and power supply to the load. 4. The system uses a fuzzy controller to control the output power of the solar panel. This Fuzzy controller analyzes input parameters such as voltage and current and adapts the operation of the MPPT controller to maximize the power supplied to the load. 5. A PI controller is used to control the charging and discharging process of the battery. It stabilizes the battery's output voltage and current, preventing it from overcharging or over-discharging. This unit ensures the reliability of the battery part of the system. 6. The system output contains visualization blocks that display the main operation parameters. This includes a graphical representation of voltage, current, and power for both the solar panel, battery, and load. This section allows you to conduct a detailed analysis of the system in real time and evaluate its effectiveness.

Results. After training and successful testing by the model system, the characteristics of the output parameters were obtained, which are shown in Figure 7.

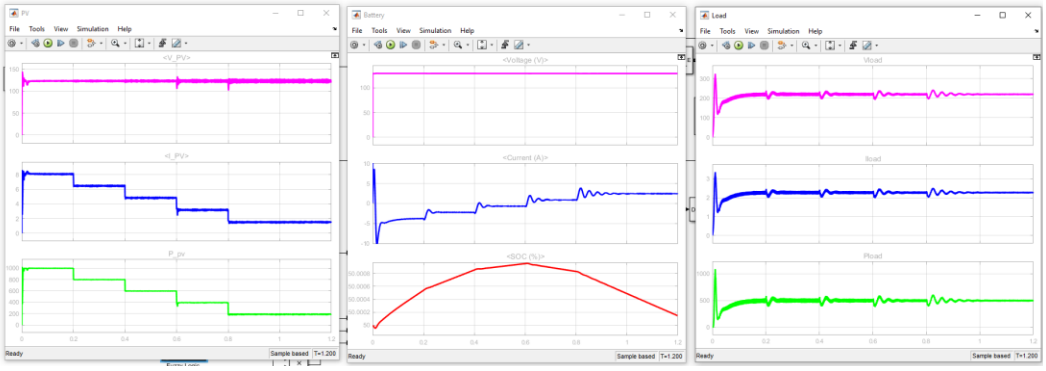

Fig.7. Characteristics of the output parameters

This image shows the results of a photovoltaic system simulation performed in MATLAB/Simulink. The graphs show the performance characteristics of the solar panel, battery, and load. The left panel (PV - solar panel) demonstrates voltage stabilization (VPV) sometime after the model is launched. Voltage fluctuations are associated with changes in light conditions and the operation of the MPPT controller. The panel current (IPV) varies stepwise depending on the controller's adaptation to changing conditions. The panel's power (PPV) also reflects the effect of incoming radiation. The central panel (Battery) shows that the battery voltage increases during charging and stabilizes when load balance is established. The battery current varies depending on the charging process and load consumption. The battery charge level (SOC) is gradually increasing, demonstrating the accumulation of energy, and decreases when it is consumed by the load. The right panel (Load - load) illustrates the stability of the load voltage (Vload), which confirms the correct operation of the regulators. Load current (Iload) and load capacity (Pload) vary depending on the parameters of the solar panel, demonstrating a correlation between energy consumption and energy production.

Discussion. The discussion of the results showed that the proposed approach has high practical significance. The use of ANFIS for photovoltaic system control provides adaptive real-time parameter control. This is especially important for low-voltage networks, where power fluctuations can lead to equipment malfunctions. Comparison with traditional management methods has shown that ANFIS provides higher forecasting accuracy and minimizes regulatory errors. This approach can be successfully applied in regions with high solar activity and difficult energy supply conditions.

Thus, the proposed model of a photovoltaic system with intelligent control based on ANFIS has proven its effectiveness. It ensures the stability and reliability of power systems, reducing the impact on low-voltage networks and increasing their energy efficiency. The developed approach can become the basis for further integration of renewable energy sources into distribution networks, contributing to their sustainable development.

Conclusions. As a result of the research, a photovoltaic system designed for load balancing in low-voltage electric networks using solar panels was developed and modeled. The main focus was on creating a fuzzy logic-based control algorithm (ANFIS), which made it possible to effectively regulate system parameters and ensure uniform load distribution.

The simulation confirmed that the proposed control algorithm demonstrates high adaptability to changing environmental conditions, including fluctuations in solar radiation and temperature. The implementation of the ANFIS algorithm made it possible to minimize transients, stabilize system operation parameters and ensure reliable power supply to the load.

The system has shown the ability not only to generate and store energy, but also to efficiently distribute it between the elements of a low-voltage network. Load balancing was achieved by stabilizing voltage, current, and power at all levels: from the solar panel to the battery and load. The integration of the battery allowed the system to store excess energy during periods of high solar activity and release it during periods of scarcity, which also helped to equalize the load profile.

Thus, the proposed approach has demonstrated effectiveness in solving the problem of load balancing in low-voltage electric networks integrated with solar panels. The results obtained confirm the prospects of the development for practical application in distributed generation and power supply systems.

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