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Development of a technological scheme for energy equipment based on renewable energy sources

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Abstract. In this article information on the development of a technological scheme for energy equipment based on renewable energy sources, with a particular emphasis on inverter-based systems. As the share of solar and hybrid power plants continues to grow, ensuring reliable power conversion, harmonic mitigation, voltage stability, and efficient integration into the electrical grid becomes critically important. The proposed technological scheme incorporates advanced inverter control methods, filtration units, energy storage interfaces, and monitoring systems that enhance overall system performance. The research outlines the structural configuration of the inverter system, its operational algorithms, and the expected improvements in energy efficiency, power quality, and system stability. The results provide a foundation for designing modern renewable-energy power plants with high reliability, reduced losses, and improved dynamic response.

INTRODUCTION

The rapid global transition toward renewable energy sources has significantly increased the demand for efficient, stable, and highly reliable power conversion systems. Solar photovoltaic (PV) plants, hybrid solar-diesel stations, and distributed generation units rely heavily on inverter technologies to interface renewable energy with the electrical grid. In addition to improving electricity performance, it is also necessary to use modern energy-saving devices and improve technological processes in accordance with the requirements of the time. Building an energy balance based on the analysis of technological processes of the enterprise, as well as forecasting electricity consumption is one of the urgent tasks. This article discusses the issues of energy conservation, efficiency improvement and forecasting in spinning workshops [1], the role of tariffs in the energy system and the creation of methods for managing and improving electricity consumption modes with the correct use of tariff periods in electricity consumption [2]. As a result, the operational quality of inverter systems-particularly their ability to regulate voltage, maintain frequency stability, mitigate harmonic distortions, and support dynamic load conditions-has become a critical research direction [3].

In Uzbekistan, where solar energy potential is among the highest in the region, the development of advanced inverter-based technological schemes is of strategic importance. The integration of renewable energy into the national grid requires innovative engineering solutions capable of ensuring power quality, reducing conversion losses, and improving system resilience under variable environmental and load conditions. This study focuses on designing and optimizing a technological scheme for energy equipment based on renewable energy sources, with an emphasis on inverter systems and their control algorithms. The work investigates modern approaches to inverter control, energy storage interaction, harmonic filtering, and grid synchronization. The proposed scheme serves as a foundation for enhancing the efficiency and reliability of renewable power plants, supporting the ongoing energy transition and sustainable development goals [4-7].

EXPERIMENTAL RESEARCH

One of the main elements of integration into the electric networks of power plants (IES) is inverter synchronization. Synchronization with the inverter allows you to synchronize the parameters of the microgrids - the amplitude, frequency and phase of the oscillations. In this jargon, antivirus software is still used as a means of protection against

viruses, hybrid viruses, and electrical viruses. The development of a technological process scheme for electrical equipment based on renewable energy sources is not only an environmentally friendly solution, but also a matter of economic efficiency, energy independence, and the stability of power supply systems. A properly designed system with automation and backup capabilities ensures reliable operation of facilities under any conditions [8-10].

TABLE 1: Harmonic Distortion Levels Compared to GOST Standard

Harmonic	Average amplitude, %	Maximum, %	Standard GOST
3rd	2.5%	7%	$\leq 5\%$
5th	3.9%	10%	$\leq 6\%$
7th	2.2%	6%	$\leq 5\%$
11th	1.3%	4%	$\leq 3\%$
13th	1.0%	3%	$\leq 3\%$
Interharmonics (20-80 Hz)	0.8%	up to 2%	not standardized
100 Hz ripple (2nd)	1.7%	5%	$\leq 3\%$

The presented table summarizes the measured harmonic distortion levels in the hybrid PV–Diesel power system and compares them with the permissible limits established by the GOST power quality standard. The data include the average amplitude, maximum recorded values, and allowable limits for the primary odd harmonics (3rd, 5th, 7th, 11th, 13th), as well as interharmonics within 20–80 Hz and the 100 Hz second harmonic (ripple).

This harmonic analysis is critical because excessive harmonic distortion can severely degrade the stability, efficiency, and power quality of hybrid renewable–diesel systems. Harmonics originate from nonlinear loads, inverter switching, diesel generator frequency fluctuations, and dynamic interactions between filters and the grid. Understanding these distortions is essential for improving system reliability and ensuring compliance with energy standards. Inverters are essential components of hybrid PV–Diesel power systems, performing the DC-to-AC conversion required to integrate renewable sources into the grid. However, the conversion process inherently introduces harmonic distortions, which can degrade the stability, efficiency, and power quality of the entire system [12,13].

The harmonics generated by the inverter arise from switching operations, nonlinear filtering processes, and dynamic interactions between the inverter, the load, and the grid. These distortions often lead to elevated Total Harmonic Distortion (THD), voltage oscillations, resonances, and excessive thermal stress on system components. High-Frequency PWM Switching. This switching produces: high-frequency harmonics, sideband, components around the switching frequency, electromagnetic noise. If the PWM frequency is too low or the output filter is improperly designed, these harmonics leak into the output voltage and current. Output filters are designed to attenuate high-frequency harmonics. Problems occur when: filter parameters are improperly selected, the filter has high quality factor (Q), leading to sharp resonance peaks, damping resistors are absent or ineffective, component tolerances cause detuning. As a result: 5th and 7th harmonics become dominant, resonance amplifies certain frequency components, THD increases significantly [14-18].

TABLE 2. Performance Parameters of Hybrid Energy System Components

Component	Power, kW	Average Daily Operating Time, h	Daily Energy, kWh
Solar Panels (PV)	10.0	5.5	55.0
Wind Generator (WG)	5.0	6.0	30.0
Diesel Generator (DG)	8.0	1.5	12.0
Consumers	12.0	24.0	288.0
Battery (BESS)	—	—	144.0

One of the major challenges faced by modern solar power plants is the mismatch between the inverter's output voltage waveform and the grid voltage parameters. This inconsistency leads to phase misalignment, frequency deviations, and increased harmonic distortion. Such distortions negatively affect the operation of grid equipment, increase power losses, and reduce the lifespan of energy system components. According to IEEE 519:2014 and GOST 32144-2013 standards, the Total Harmonic Distortion (THD) at the Point of Common Coupling must not exceed 5%. However, in many inverter systems, this value is significantly higher due to insufficient control strategies and imperfect filtering mechanisms. There are two options for technical solutions to stabilize the frequency of the output voltage. The first option is a direct mechanical effect on the rotation speed of the wind wheel, which is technically

possible, for example, it is necessary to change the angle of the blades. The second option is to convert non-standard energy into standard electricity [19-21].

The mismatch between the inverter's sine wave and the grid sine wave becomes particularly noticeable under conditions of fluctuating solar irradiance, temperature variations, load asymmetry, and the presence of nonlinear loads. Under such circumstances, even small phase shifts ($2-5^\circ$) can lead to oscillations in active and reactive power, overloads, and a reduction in inverter efficiency. Recent studies show that harmonic distortion exceeding 8–10% results in excessive heating of transformers and reactors, a 3–5% decrease in efficiency, and accelerated failure of electrical equipment [22-26].

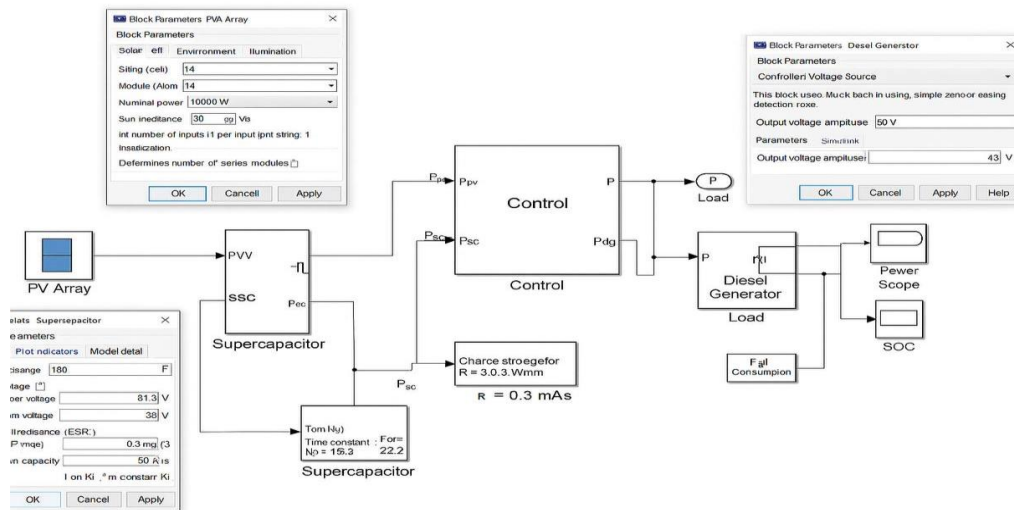


FIGURE 2. Model of a hybrid solar–diesel power plant with supercapacitors in the MATLAB/Simulink environment.

The presented MATLAB/Simulink model illustrates the structure and operational interaction of a hybrid solar–diesel power plant integrated with a supercapacitor energy-storage module. The system consists of several interconnected subsystems, each responsible for energy generation, storage, conversion, and load supply.

The PV Array block generates electrical power based on solar irradiation and temperature inputs. Its parameters include:

- Number of series strings
- Cells per string
- Irradiance (W/m^2)
- Temperature ($^\circ\text{C}$)

A dedicated *Supercapacitor* block is used to stabilize rapid power fluctuations. Its parameters include capacitance, initial voltage, internal resistance (ESR), and nominal energy capacity.

The supercapacitor exchanges power (P_{SC}) with the control system to support transient load variations and mitigate voltage dips.

The central *Control* block receives inputs from both the PV array (P_{PV}) and the supercapacitor (P_{SC}) and determines the optimal distribution of power to the load. It also governs the activation of the diesel generator, depending on the load demand and renewable-energy availability.

Control outputs include:

- P_{dg} — power command for the diesel generator
- P — regulated output power delivered to the load

The *Diesel Generator* block operates as a backup power source when renewable energy is insufficient. It includes:

- Voltage source control
- Output voltage amplitude settings
- Fuel-consumption monitoring

Its generated power complements the PV array and supercapacitor to ensure uninterrupted load supply.

The system supplies power to a dynamic *Load* block. Additional monitoring components include:

- *Fuel Consumption* indicator
- *Power Scope* for output-waveform visualization
- *SOC* (State of Charge) display for the supercapacitor
- These tools allow analysis of the system's stability, power quality, and efficiency.

Therefore, the study of generating and synchronizing the sinusoidal output voltage of solar plant inverters represents a highly relevant scientific and technical task aimed at improving power quality, operational stability, and the overall efficiency of solar power plants. The development of new filtering and control algorithms that comply with IEEE and IEC international standards is of great importance for integrating solar power plants into modern smart grids and ensuring the reliable operation of distributed generation systems.[6]

RESEARCH RESULTS

In the spectral analysis of the PWM signal, along with the fundamental sinusoidal frequency f_1 , high-frequency harmonics are also present:

$$U(f) = U_1(f_1) + \sum_{n=2}^{\infty} U_n(f_c \pm nf_1) \quad (1)$$

Theoretical Model of the Filtering System

To filter the output signal of the inverter, LC or LCL filters are commonly used. These filters suppress high-frequency harmonics and bring the output voltage closer to grid-quality standards.[3-4]

Differential Equations of the LC Filter

$$L \frac{di_L}{dt} = U_{inv} - u_c \quad (2)$$

$$C \frac{du_c}{dt} = i_L - i_{load} \quad (3)$$

In hybrid solar–diesel power plants, the stability and quality of power supply are directly dependent on the performance of the inverter. During the conversion of direct current (DC) into alternating current (AC), the inverter generates a pulse-width modulation (PWM) signal. However, the resulting output voltage is not an ideal sinusoid—it contains high-frequency harmonic distortions. This degrades the quality of electrical energy, increases reactive power, and negatively affects the operation of consumer equipment.

Therefore, it is necessary to filter and optimize the inverter output voltage through intelligent control. For this purpose, a flexible control algorithm is developed to coordinate energy sources and filter components within the hybrid station.

The main objective of the control algorithm is to ensure the sinusoidality of the voltage delivered to the grid and maintain the Total Harmonic Distortion (THD) value below 5%.

The algorithm performs the following tasks:

- optimal control of the inverter's PWM modulation;
- suppression of high-frequency harmonics using an LCL filter;
- compensation of reactive power;
- coordination of battery and supercapacitor operation;
- phase synchronization with the grid (based on PLL).

In a photovoltaic hybrid power system (PVHPS), analysis of load conditions is essential for effective design, operation, and control. In a solar–diesel hybrid power plant, loads may vary depending on several factors, including solar irradiance, climatic conditions, energy demand, and the operational characteristics of the diesel generator.

Mathematical Expression of Synchronization

To ensure phase alignment between the inverter and the grid, a Phase-Locked Loop (PLL) is used. Its fundamental equation is as follows:

$$\theta_{err}(t) = \theta_{grid}(t) - \theta_{inv}(t) \quad (4)$$

$$\frac{d^2 \theta_{inv}(t)}{dt^2} = \omega_0 + K_p \theta_{err}(t) + K_i \int \theta_{err}(t) dt \quad (5)$$

For THD and resonance control, when selecting $C_f L_1 L_2$ choose the resonance frequency f_{res} much lower than the PWM carrier frequency, but higher than the network harmonics.

$$f_{res} \approx \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C_f}} \quad (6)$$

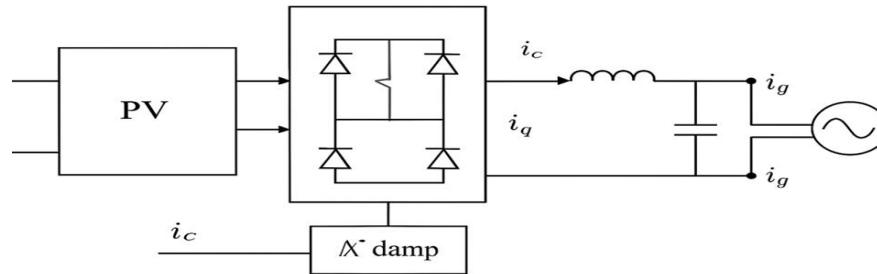


FIGURE 3. Principal schematic diagram of the voltage-filtering device for the inverter output in solar–diesel power plants.

The research was carried out on a laboratory-scale hybrid system consisting of the following components:

PV Array – nominal power 1.5 kW, output voltage 48 V.

Diesel Generator (DG) – 2.5 kW, 220 V, 50 Hz.

Inverter (DC/AC Converter) – operates based on sinusoidal PWM (SPWM) and is equipped with an LC filter at the output.

Automatic Voltage Regulator (AVR Controller) – microcontroller-based, providing adaptive control for voltage phase and amplitude variations.

Load Bank – a combination of resistive and inductive loads within the 0.5–2 kW range.

Monitoring System (SCADA/IoT) – collects real-time data on current, voltage, phase, and frequency.

The system was tested under nominal conditions of 220 V and 50 Hz. During experiments with rapidly varying solar irradiance (600–900 W/m²) and diesel generator frequency fluctuations (49–51 Hz), the following results were obtained:

TABLE 2. Comparison of System Performance With and Without Controller

Parameter	Without Controller	With Controller	Difference (%)
Voltage fluctuation amplitude, V	±18	±5	↓72%
Phase error, °	4.2	1.3	↓69%
THD (Total Harmonic Distortion), %	7.5	2.1	↓72%
Response time, ms	180	65	↓64%

The table provides a comparative analysis of the hybrid PV–Diesel power system with and without the automatic voltage regulator (AVR Controller). Four key performance indicators were evaluated: voltage fluctuation amplitude, phase error, total harmonic distortion (THD), and system response time. The results clearly demonstrate significant improvements gained through the implementation of the controller [27-56]. **Voltage Fluctuation Amplitude:** The voltage ripple was reduced from ±18 V to ±5 V, corresponding to a 72% improvement. This indicates enhanced voltage stability under varying generation and load conditions. **Phase Error:** The phase error decreased from 4.2° to 1.3°, showing a 69% reduction. This reflects better synchronization of the inverter with the grid and lower risk of phase-related instability. **THD (Total Harmonic Distortion):** Harmonic distortion decreased from 7.5% to 2.1%, resulting in a 72% improvement. This confirms that the controller effectively suppresses higher-order harmonics and significantly enhances the quality of the output sinusoidal waveform. **Response Time:** The system response time improved from 180 ms to 65 ms, equivalent to a 64% reduction. This is crucial for hybrid systems where solar irradiance and load conditions may change rapidly.

After a comparative analysis with and without a regulator, the graph below shows the output voltage of the hybrid power plant inverter using filters and its effectiveness in smoothing the sine wave.

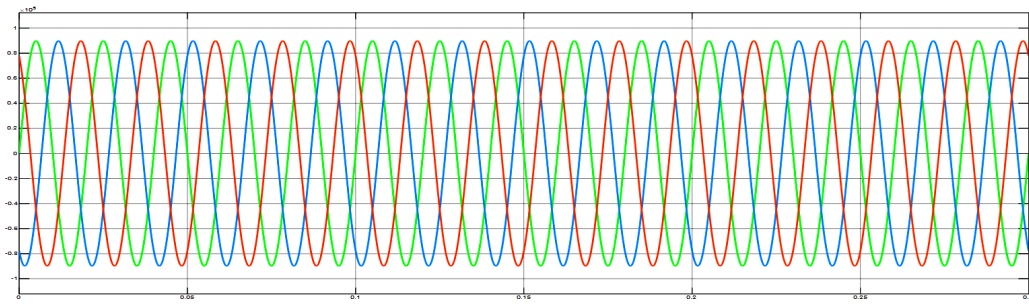


FIGURE 4. The variation of electrical energy in the three phases output from the solar power plant inverter is smoothed using an LC filter.

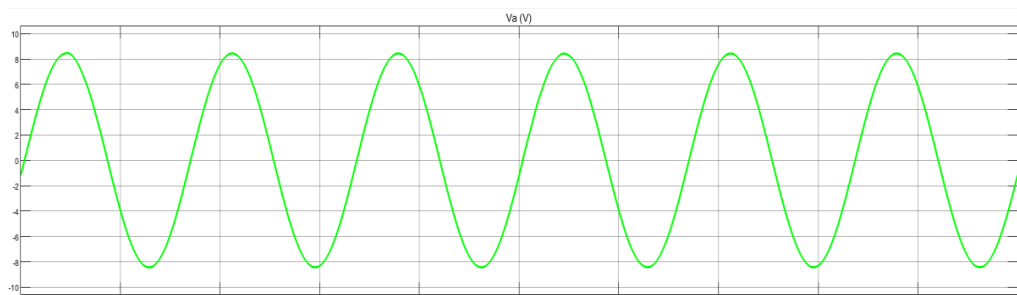


FIGURE 5. The variation of electrical energy in a single phase at the output of the solar power plant inverter is smoothed using an LC filter.

The study of generating and synchronizing the sinusoidal output voltage of solar power plant inverters is a highly relevant scientific and technical task aimed at improving power quality, operational stability, and the overall efficiency of solar power plants. The development of new filtering and control algorithms that comply with IEEE and IEC international standards is crucial for integrating solar power plants into modern smart grids and ensuring the reliable operation of distributed generation.

CONCLUSIONS

This research demonstrates that improving the sinusoidal quality and synchronization accuracy of inverter output voltage is essential for enhancing the stability, efficiency, and power quality of solar power plants. The analysis of inverter operation revealed that high-frequency harmonic distortions, phase mismatch, and voltage fluctuations significantly reduce system performance and negatively affect the reliability of grid-connected equipment. The study shows that the application of advanced filtering structures, particularly LC and LCL filters, effectively suppresses switching harmonics and reduces the Total Harmonic Distortion (THD) to values that comply with IEEE and IEC standards. Furthermore, the implementation of enhanced inverter control algorithms—such as adaptive PWM modulation, phase-locked loop (PLL) synchronization, and active damping—leads to improved dynamic response, reduced reactive power flow, and greater overall operational stability. Integrating supercapacitors and batteries into the hybrid solar–diesel system further contributes to transient stability, compensates for load variations, and smooths the power output under fluctuating environmental conditions. The developed control strategy provides flexible power management, ensuring optimal coordination between renewable sources, diesel generation, and energy-storage units.

Overall, the proposed technological and algorithmic improvements serve as a foundation for the reliable operation of modern hybrid power plants and their seamless integration into smart grid infrastructures. The results of this work can be applied to the design, modeling, and optimization of next-generation photovoltaic and hybrid energy systems.

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