Integratsiyalashgan batareya va superkondensator tizimidan foydalangan holda gibrid elektr stansiyalarda chiqish kuchlanishining sifatini yaxshilash

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Dolzarbligi: Ushbu maqolada akkumulator batareyalari (AKB) va superkondensatorlarning integratsiyalashgan gibrid energiya saqlash tizimi asosida ishlovchi quyosh–dizel elektr stansiyalarida elektr energiyasi sifati va barqarorligini oshirishga qaratilgan. Gibrid elektr stansiyalarida asosiy muammo – invertor chiqishidagi kuchlanishning tez o‘zgarishi, yuklamaning dinamik tebranishlari, qayta tiklanuvchi manbalar (quyosh radiatsiyasi) o‘zgaruvchanligi, hamda nochiziqlik yuklamalar ta’sirida yuzaga keluvchi garmonik buzilishlardir. Bu omillar THD oshishi, fazaviy xatolar va o‘rtacha kvadrat kuchlanishning barqaror emasligiga olib keladi; natijada iste’molchilarning uskunalari ish rejimida uzilishlar, energiya samaradorligining pasayishi va dizel generatorning ortiqcha ishlash sikllariga sabab bo‘ladi

Maqsad: kuchlanishning tez o‘zgarishlari, pik yuklamalar va garmonikalarni yumshatish orqali tarmoqka beriluvchi elektr energiyasining sifatini yaxshilashdir (THD kamayishi, fazaviy xato va amplituda barqarorligi).

Usullari: xalqaro tajriba va talabni boshqarishning qiyosiy tahlil usullaridan foydalaniladi.

Natijalar: Akkumulyator batareyalari va superkondensatorlarni integratsiyalashgan holda qo‘llash gibrid elektr stansiyalarida:kuchlanish barqarorligini oshirish,garmonik buzilishlarni kamaytirish,AKB xizmat muddatini uzaytirish,dizel generator sarfini kamaytirish kabi muhim afzalliklar beradi. Bu yechim zaif tarmoqlar, avtonom qishloq elektrlashtirishi, sanoat ob’ektlari va Smart Grid tizimlarda qo‘llash uchun juda samarali hisoblanadi.

Kalit so‘zlar: Smart grid tizimi, SCADA, oqilona energiya iste’moli, quyosh-dizel elektr stansiyasi, avtomatik tartibga solish, energiya manbalarini almashtirish, Arduino mikrokontrolleri, gibrid energetik tizim.

Повышение качества выходного напряжения на гибридных электростанциях с использованием интегрированной системы аккумуляторов и суперконденсаторов

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Актуальность: в данной статье рассматривается повышение качества и стабильности электрической энергии в солнечно-дизельных гибридных электростанциях за счёт применения интегрированной гибридной системы хранения энергии на основе аккумуляторных батарей (АКБ) и суперконденсаторов. Основной проблемой гибридных электростанций являются быстрые колебания выходного напряжения инвертора, динамические изменения нагрузки, вариативность возобновляемых источников энергии (солнечной радиации), а также гармонические искажения, возникающие под воздействием нелинейных нагрузок. Эти факторы приводят к увеличению коэффициента гармонических искажений (THD), фазовым ошибкам и нестабильности среднеквадратичного значения напряжения; в результате возникают сбои в работе потребительского оборудования, снижается энергетическая эффективность и увеличивается число избыточных рабочих циклов дизель-генератора.

Цель: повышение качества электроэнергии, подаваемой в сеть, за счет снижения быстрых колебаний напряжения, пиковых нагрузок и гармоник (снижение коэффициента гармонических искажений, фазовой погрешности и стабильности амплитуды).

Методы: используется международный опыт и сравнительный анализ методов управления спросом.

Результаты: комплексное использование аккумуляторных батарей и суперконденсаторов в гибридных электростанциях обеспечивает значительные преимущества, такие как повышение стабильности напряжения, снижение гармонических искажений, увеличение срока службы аккумуляторной батареи и снижение потребления электроэнергии дизель-генератором. Данное решение весьма эффективно для использования в слаботочных сетях, автономной электроснабжении сельских районов, промышленных объектах и системах Smart Grid.

Ключевые слова: ситема smart grid,SCADA, рациональное энергопотребление, солнечно-дизельная электростанция, автоматическое регулирование, переключение источников энергии, микроконтроллер Arduino, гибридная энергосистема.

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Improving the output voltage quality in hybrid power plants using an integrated battery and supercapacitor system

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Relevance: this article examines improving the quality and stability of electrical energy in solar-diesel hybrid power plants through the use of an integrated hybrid energy storage system based on batteries and supercapacitors. The main challenges of hybrid power plants include rapid fluctuations in inverter output voltage, dynamic load changes, variability in renewable energy sources (solar radiation), and harmonic distortion caused by nonlinear loads. These factors lead to increased total harmonic distortion (THD), phase errors, and RMS voltage instability. These factors lead to malfunctions in consumer equipment, reduced energy efficiency, and increased diesel generator over-runs.
Aim: improving the quality of electrical energy supplied to the grid by reducing rapid voltage fluctuations, peak loads and harmonics (reducing the harmonic distortion coefficient, phase error and amplitude stability).
Methods: international experience and methods of comparative analysis of demand management are used.
Results: the combined use of batteries and supercapacitors in hybrid power plants offers significant benefits, including improved voltage stability, reduced harmonic distortion, extended battery life, and reduced diesel generator power consumption. This solution is highly effective for use in low-voltage grids, autonomous power supply for rural areas, industrial facilities, and Smart Grid systems..
Keywords: EPS, energy transition, wind and solar generation, demand response, deficit modes, mode balancing, contractual relations, consumer-regulators.

1. Introduction

In the modern world, electricity is one of the most essential resources, supporting every sphere of human activity. Like any other commodity, electricity is subject to quality requirements. However, it has unique characteristics: its parameters can vary over time, and in case of complaints, it cannot be returned or exchanged. Furthermore, the quality of electricity may depend on the requirements of the specific consumer [1].

The main goal of the Concept is to meet the growing demand for electricity at competitive prices and to ensure the dynamic development of the country's power sector through the modernization and reconstruction of existing power plants, the construction of new generation facilities based on high-efficiency technologies, the improvement of electricity metering systems, and the diversification of fuel and energy resources, including the development of renewable energy sources (RES).

In most developed countries around the world, renewable energy sources are increasingly being used for electricity generation, with their share exceeding 20% in some countries. In this context, the study of power quality parameters and dynamic characteristics of operating modes of photovoltaic power plants (PVPPs), when operating in parallel with traditional power systems, is highly relevant.

To achieve a reliable control system for the entire electricity generation process, it is essential to integrate all components responsible for energy production, transmission, and distribution into a unified system - up to the end consumers. Such integration is necessary to ensure data synchronization and thorough analysis of all possible processes. This requirement is addressed by the concept of Smart Grids.

The essence of a Smart Grid lies not only in the delivery of electricity to various categories of consumers but also in data collection. Based on the collected data, the system allows for real-time tariff accounting, forecasting, and planning of electricity consumption and generation [2]. The intelligent control system also facilitates the integration of traditional energy sources with non-traditional renewable energy sources. This includes the hybrid operation of thermal power plants (TPPs), hydroelectric power plants (HPPs), nuclear power plants (NPPs), and diesel power plants (DPPs) with solar power plants (PVPPs), wind power plants (WPPs), and other renewable energy sources (RES) [3].

2. Methods and materials

In the context of the global transition to sustainable energy sources, the integration of solar-diesel hybrid systems (SDHPPs) into smart grids is becoming increasingly important. The combination of photovoltaics, diesel generators, and energy storage systems ensures energy supply reliability and flexibility in remote and unstable regions. A Smart Grid is an intelligent energy infrastructure that provides two-way communication between energy producers and consumers. The implementation of

SDHPPs into such systems not only decentralizes power generation but also enables adaptive resource management. Hybrid solar-diesel power plants represent an increasingly viable solution for ensuring reliable electricity supply in remote or off-grid areas. By integrating photovoltaic (PV) systems with conventional diesel generators, these plants leverage the advantages of both renewable and traditional energy sources. This combination enables consistent power generation while reducing fuel consumption, operational costs, and greenhouse gas emissions.

In typical operation, solar energy is prioritized during daylight hours, powering the load directly and, when integrated with battery storage systems, charging them for later use. When solar irradiance is insufficient—due to weather conditions or during nighttime—the diesel generator compensates for the shortfall, ensuring uninterrupted energy supply. The use of advanced energy management systems allows for the intelligent coordination of energy flows between the solar PV array, diesel generator, storage systems, and the load. These systems monitor energy production and consumption in real time, optimizing the plant's efficiency and minimizing the runtime of diesel generators[3].

Structure of a Solar-Diesel Hybrid System

- A typical SDHPP includes:
- Photovoltaic panels (PV)
- Diesel generator
- Energy storage system (batteries and/or supercapacitors)
- Inverter and controller
- SCADA system for monitoring and control

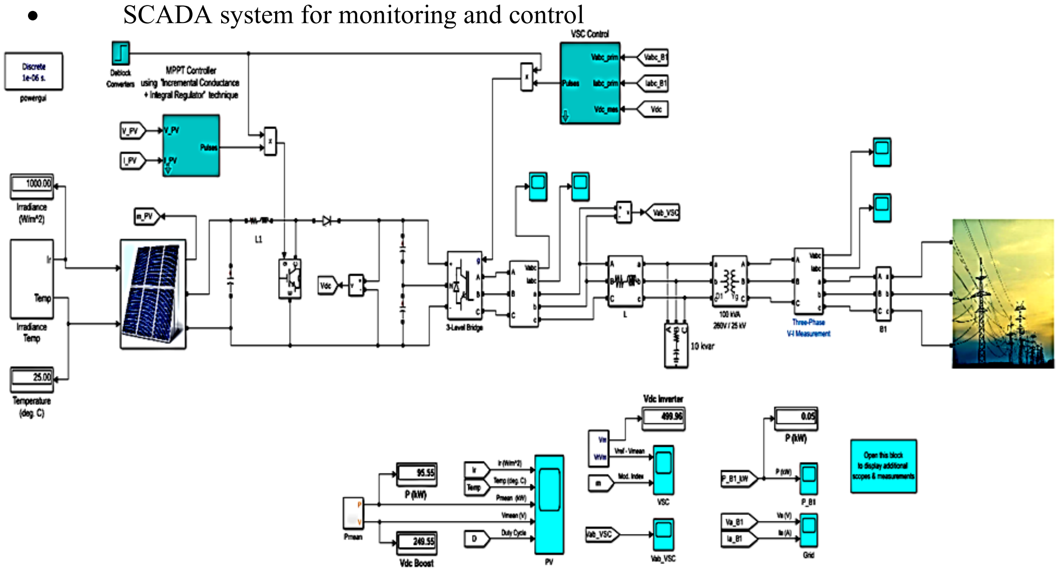

Fig.1 A simulation model of the inverter device of a solar-diesel power plant assembled in the Matlab/Simulink software package

The energy balance can be described by the equation:

$$P_{load}(t) = P_{PV}(t) + P_{DG}(t) + P_{bat}(t) \pm \Delta P(t); \quad (1)$$

where $P_{load}(t)$ is the load at time t, $P_{PV}(t)$ is the power from the solar plant, $P_{DG}(t)$ is the power from the diesel generator, $P_{bat}(t)$ is the power from the battery, and $\Delta P(t)$ represents energy losses.

Reduction of harmonic effects between inverter and diesel generator.

$$V_{sys}(t) = V_{PV}(t) + V_{DG}(t) - \Delta V_{loss}(t)\ . \quad (2)$$

The output signal of the automatic regulator for voltage stabilization is determined according to the following law:

$$U_{ctrl}(t) = K_p \cdot e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}\ ; \quad (3)$$

where:$e(t) = V_{ref} - V_{sys}(t)$- error,$K_p K_i K_d$- proportional, integral and differential coefficients of the controller.

Integrating SDHPPs into the Smart Grid requires:

- frequency and voltage synchronization with the grid;
- implementation of intelligent control (e.g., predictive regulation);
- capability to store and inject energy into the grid.

Example of Energy Flow Control Algorithm. The control algorithm can be implemented as follows:

Monitor parameters: P_{PV}, P_{load}, SOC;

If $P_{PV} > P_{load}$, the excess goes to charge the battery;

If $P_{PV} + P_{bat} < P_{\_load}$, the diesel generator is started;
If SOC is low, the system switches to economy mode.

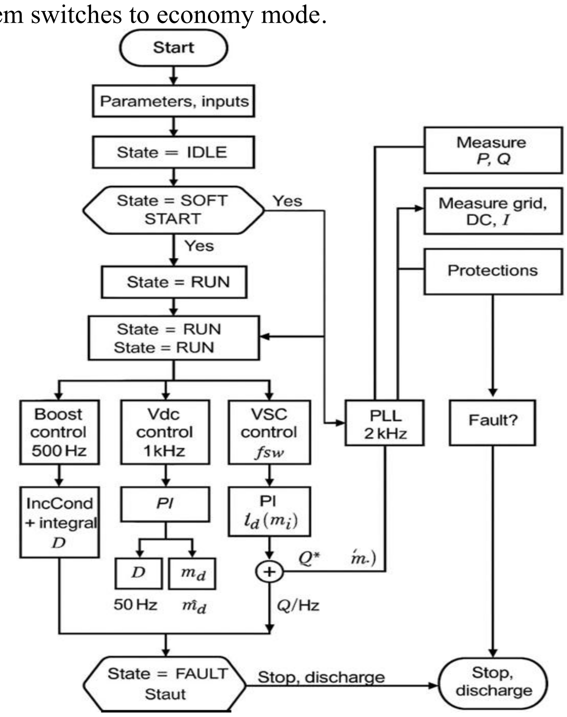

Fig.2 An algorithm for the operation of a solar-diesel power plant integrating batteries and supercapacitors

Remote control algorithm. The control system operates in two modes:
1. Auto Mode:
The controller decides on the BESS, inverter and diesel generator mode based on sensor data; For example, if the output power from the solar panels is low, the diesel generator or battery is activated.
2. Manual Mode:
The operator controls each device separately via SCADA (for example, turning on/off the diesel, estarting the inverter).

Control law (for automatic voltage adjustment):

$$U_{ref} = U_0 + k_p(P_{set} - P_{meas}) + k_1 \int (P_{set} - P_{meas})dt \,. \quad (4)$$

Through this formula, voltage is automatically corrected for power deviations. Generation suitable for covering peak loads should have other "useful" properties:
be dispatched, that is, controlled by a person;
to be as maneuverable as possible, that is, capable of delivering energy to the network in minutes, and sometimes even seconds, and not fail with an equally rapid shutdown;
have minimal capital costs.
While intermittent alternative generation is a fraction of a percent of the dispatched generation, its saw is simply lost in the general "noise". This does not mean that the harm from intermittent alternative generation is absent at its small fraction, it means that the harm is so small that it can be neglected, but only in this case, any possible "help" from intermittent alternative generation is also so small that it can also be neglected.

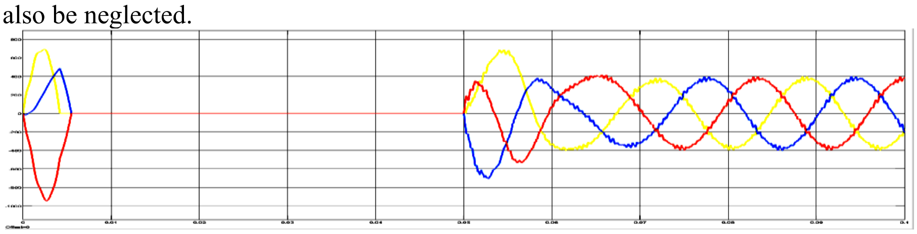

Fig.3 Parameters of the simulation model of the inverter device of a solar-diesel power plant assembled in the Matlab/Simulink software package.

There are a number of methods that can be used to solve intermittent alternate generation problems, i.e. methods of balancing an emerging production saw: overproduction of alternative energy; expansion of networks; demand management; energy storage; duplication of traditional generating energy.

3. Results and discussion

To evaluate the efficiency of different operating modes of a Solar-Diesel Hybrid Power Plant (SDHPP), a comparative analysis was conducted for four configurations: diesel-only mode, solar-diesel mode, SDHPP with battery storage, and SDHPP with both battery and supercapacitor.

Table 1. Comparison of SDES operating modes

Mode	Fuel Consumption (L/day)	Diesel Operation Time (h/day)	Battery Wear (%)
Diesel Only	40	24	0
Solar-Diesel	20	12	5
SDHPP with Battery	10	6	10
SDHPP with Battery and Supercapacitor	6	4	3

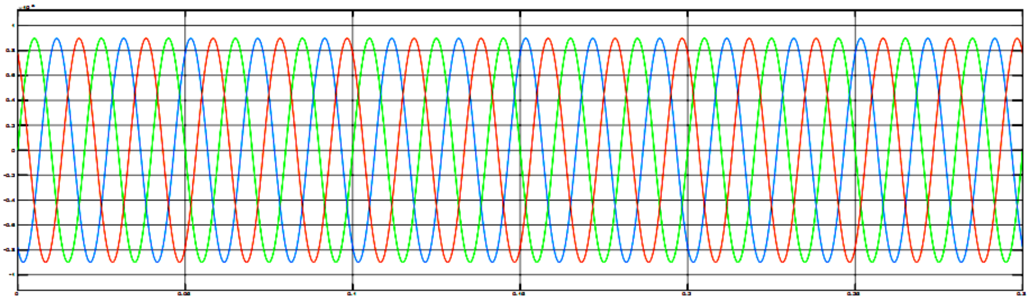

Fig.4 Graph comparing different operating modes of a solar-diesel hybrid power plant (SDHPP) on three parameters: fuel consumption (l/day), diesel runtime (hrs/day) ,battery wear (%)

Fuel Efficiency: The best performance is shown by the system with both a battery and a supercapacitor, reducing fuel consumption by 85% compared to the diesel-only mode.

• Diesel Generator Runtime: Significantly reduced operation time extends the equipment's service life and lowers maintenance costs.

• Battery Longevity: Integrating a supercapacitor reduces the load on the battery, minimizing degradation and increasing its lifespan.

• Thus, the most efficient and reliable configuration is the combined use of batteries and supercapacitors, which ensures high energy efficiency and stable power supply performance.

In this table, a comparative analysis of the basic indicators of the hybrid system with integrated AKB and supercapacitors is introduced.

Table 2. Comparative analysis of controllers without filtration and use of AKB and supercapacitors

Indicator	Without Monitoring	With Monitoring	Percentage Change
Downtime	4,2 h/m	1,3 h/m	↓ 69%
Response time	90 c	25 c	↓ 72%
Energy efficiency	83 %	92 %	↑ 9%

4. Conclusion

Hybrid solar-diesel power plants offer a practical and effective approach to addressing the challenges of energy access, fuel dependency, and environmental sustainability in off-grid locations. By combining the strengths of solar power and diesel generation, these systems ensure a reliable power supply while minimizing environmental and economic costs. With ongoing advancements in technology and decreasing costs of solar components, hybrid energy systems are poised to play a key role in the future of decentralized and sustainable energy infrastructure. Analysis of information on this topic showed that there are a number of requirements for the quality of electrical energy, which are determined by the increasingly high level of use of high-tech industries in various sectors of agriculture. This is especially important for alternative generation at wind turbines, biogas stations (internal combustion engine generation) and solar power plants. There are a number of ways to improve the quality of electricity to increase the efficiency of energy supply to consumers, such as reactive power compensation devices, synchronous compensators, inverter devices, etc. It should be noted that the use of these devices is individual in each case and the choice should be made on the basis of a feasibility study. The main indicators of power quality are parameters such as voltage, frequency and harmonic distortion.

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