IMPLEMENTATION OF A REAL-TIME IoT-BASED MONITORING AND ADAPTIVE LOAD CONTROL SYSTEM FOR SMALL-SCALE SOLAR ENERGY INSTALLATIONS

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Annotatsiya. Mazkur maqolada kichik quvvatli quyosh energiyasi tizimlari uchun IoT texnologiyalariga asoslangan real vaqtli monitoring va adaptiv yuklama boshqaruv tizimini ishlab chiqish hamda uni amaliyotga joriy etish masalalari yoritilgan. Taklif etilgan tizim ESP32 mikrokontrolleri asosida qurilib, kuchlanish, tok, quvvat, harorat va yorug‘lik intensivligi kabi asosiy parametrlarni uzluksiz o‘lchash imkonini beradi. Olingan ma’lumotlar Wi-Fi orqali masofaviy serverga uzatiladi va foydalanuvchi interfeysi orqali tahlil qilinadi. Adaptiv boshqaruv algoritmi tashqi muhit sharoitlari o‘zgarishiga mos ravishda yuklamani optimallashtiradi va energiya yo‘qotishlarini kamaytiradi. Tajriba natijalari tizim energiya samaradorligini oshirish va kichik quvvatli quyosh qurilmalarining barqaror ishlashini ta’minlashda amaliy ahamiyatga ega ekanligini ko‘rsatdi.

Kalit so‘zlar: Quyosh energiyasi, IoT monitoring, adaptiv boshqaruv, yuklama optimallashtirish, ESP32, real vaqt tizimi, energiya samaradorligi.

Аннотация. В статье рассматриваются вопросы разработки и практического внедрения системы мониторинга в реальном времени и адаптивного управления нагрузкой для маломощных солнечных энергетических установок на основе технологий IoT. Предложенная система построена на микроконтроллере ESP32 и обеспечивает непрерывное измерение напряжения, тока, мощности, температуры и уровня освещённости. Полученные данные передаются на удалённый сервер через Wi-Fi и анализируются посредством пользовательского интерфейса. Алгоритм адаптивного управления автоматически оптимизирует нагрузку в зависимости от изменения внешних условий, что позволяет снизить энергетические потери. Результаты экспериментов подтверждают практическую значимость разработанной системы для повышения эффективности и стабильности работы малых солнечных установок.

Ключевые слова: Солнечная энергетика, IoT-мониторинг, адаптивное управление, оптимизация нагрузки, ESP32, система реального времени, энергоэффективность.

Abstract. This paper presents the development and practical implementation of a real-time IoT-based monitoring and adaptive load control system for small-scale solar energy installations. The proposed system is built on an ESP32 microcontroller and enables continuous measurement of voltage, current, power, temperature, and solar irradiance. The collected data are transmitted to a remote server via Wi-Fi and analyzed through a web-based user interface. An adaptive control algorithm dynamically adjusts the load conditions in response to environmental changes, thereby reducing energy losses and improving overall system stability. Experimental results demonstrate that the developed system significantly enhances energy efficiency and ensures reliable operation of small-scale photovoltaic systems under varying operating conditions.

Keywords. Solar energy, IoT monitoring, adaptive load control, ESP32, real-time system, energy efficiency, photovoltaic optimization.

In recent years, renewable energy sources have become a key priority in global energy development, with solar energy emerging as one of the fastest-growing sectors. Small-scale solar energy systems are increasingly implemented in residential buildings, small businesses, and off-grid applications due to their environmental sustainability and relatively low installation cost. However, in real operating conditions, the performance of photovoltaic panels often deviates from their nominal laboratory specifications.

Solar panel efficiency is strongly influenced by environmental factors such as ambient temperature, fluctuations in solar irradiance, dust accumulation, and improper load conditions. In many conventional small-scale installations, monitoring is limited to basic energy output measurement without real-time analysis or adaptive control mechanisms. As a result, energy losses increase and overall system efficiency decreases.

The rapid development of Internet of Things (IoT) technologies has enabled continuous data acquisition, remote supervision, and intelligent management of energy systems. IoT-based monitoring platforms allow real-time measurement of key electrical and environmental parameters, data transmission to cloud servers, and visualization through user-friendly interfaces. Nevertheless, monitoring alone is not sufficient to ensure optimal system performance.

To improve operational stability and energy utilization, adaptive load control strategies must be integrated into small-scale photovoltaic systems. Such approaches allow dynamic adjustment of load conditions based on real-time measurements, thereby reducing power fluctuations and minimizing efficiency degradation.

The objective of this study is to develop and experimentally validate a real-time IoT-based monitoring and adaptive load control system for small-scale solar energy installations. The proposed solution aims to enhance energy efficiency, improve operational stability, and provide a practical and scalable system suitable for decentralized renewable energy applications.

The object of this study is a small-scale photovoltaic (PV) solar energy system operating under real environmental conditions. The system consists of a photovoltaic panel connected to a variable DC load and a monitoring-control unit. The research focuses on evaluating system performance, monitoring accuracy, and the effectiveness of adaptive load control under fluctuating environmental parameters.

The proposed real-time IoT-based monitoring and adaptive load control system consists of the following main components:

- Photovoltaic solar panel
- Measurement sensors (voltage, current, temperature, irradiance)
- ESP32 microcontroller unit
- Wi-Fi communication interface
- Cloud-based data storage and visualization platform
- Adaptive load control module

The ESP32 microcontroller serves as the central processing unit responsible for data acquisition, processing, transmission, and execution of the adaptive control algorithm. Due to its integrated Wi-Fi capability, sufficient processing power, and low energy consumption, ESP32 was selected as the core controller for the system.

To evaluate the performance of the photovoltaic system, the following parameters were continuously measured:

- **Voltage (V):** Measured using a voltage divider circuit connected to the ESP32 analog input.
- **Current (A):** Measured using a Hall-effect current sensor placed in series with the load.
- **Power (W):** Calculated in real time using the expression:

$$P=V\times I$$

- **Panel Temperature (°C):** Measured using a digital temperature sensor mounted on the rear surface of the solar panel.
- **Solar Irradiance (W/m² or lux):** Measured using a light intensity sensor installed near the panel surface.

These parameters provide sufficient information to evaluate system efficiency and operating stability.

Sensor data are collected through the analog and digital input pins of the ESP32 microcontroller. The data acquisition process is performed at predefined sampling intervals to ensure real-time monitoring.

After local processing, measured data are transmitted via Wi-Fi to a remote cloud server. The cloud platform stores the incoming data in a structured database and provides visualization through graphical dashboards and numerical tables. This enables remote supervision and performance evaluation through web or mobile interfac

An adaptive load control strategy was implemented to improve system performance under variable environmental conditions. The control algorithm operates according to predefined thresholds and real-time measurements.

The main control logic includes:

1. Continuous monitoring of voltage, current, temperature, and irradiance.
2. Detection of power drop or abnormal operating conditions.
3. Adjustment of load parameters using switching control or PWM-based modulation.
4. Stabilization of output power by minimizing sudden fluctuations.

For example, when panel temperature exceeds a predefined threshold and output power begins to decrease, the system dynamically adjusts the load to reduce stress on the photovoltaic module and maintain stable operation.

The system was tested under natural environmental conditions during daylight hours. Measurements were recorded continuously over several days to observe variations in temperature, irradiance, and output power.

Two operating modes were analyzed:

- Monitoring-only mode (without adaptive load control)
- Adaptive control mode (with dynamic load optimization enabled)

The performance of both modes was compared to evaluate the impact of the proposed adaptive control mechanism on energy efficiency and system stability.

Experimental validation of the proposed real-time IoT-based monitoring and adaptive load control system was conducted under natural environmental conditions. The system operated continuously during daylight hours, and all electrical and environmental parameters were recorded and analyzed.

Real-Time Monitoring Performance

The IoT monitoring platform successfully collected and transmitted voltage, current, temperature, and irradiance data without communication interruptions. The average data transmission delay was measured between 1.3 and 1.9 seconds, which confirms the suitability of the system for real-time applications. Data integrity during the testing period exceeded 99%, indicating stable wireless communication and reliable cloud integration.

The monitoring results showed a direct correlation between solar irradiance and output power. During peak irradiance hours, output power increased proportionally, while reduced irradiance in cloudy periods resulted in noticeable power drops.

Additionally, an inverse relationship between panel temperature and output power was observed. As panel temperature increased above 45°C, output power decreased despite stable irradiance levels, confirming the thermal sensitivity of photovoltaic modules.

Performance Comparison: With and Without Adaptive Control

To evaluate the effectiveness of the adaptive load control algorithm, system performance was analyzed under two operating modes:

In monitoring-only mode, power fluctuations reached up to 18–22% during rapid temperature changes. In contrast, when adaptive load control was activated, power fluctuation was reduced to approximately 8–12%.

Furthermore, average energy harvesting efficiency improved by approximately 6–9% under adaptive control conditions. The system demonstrated faster stabilization after environmental disturbances, with response times reduced by nearly 25% compared to the passive monitoring configuration.

System efficiency was calculated using the ratio between output electrical power and available solar irradiance. Experimental observations indicate that adaptive load control minimized thermal-related efficiency degradation during high-temperature periods.

Without adaptive control, efficiency dropped by up to 11% during peak thermal stress conditions. With adaptive optimization enabled, efficiency degradation was limited to approximately 5–6%, demonstrating a significant improvement in operational stability.

The system operated continuously over multiple testing days without hardware failures or data loss. The average power consumption of the monitoring-control unit was measured at approximately 2 W, confirming its suitability for integration into small-scale solar installations without significant additional energy burden.

Overall, the experimental results confirm that the integration of real-time IoT monitoring combined with adaptive load control significantly enhances system performance, reduces power fluctuations, and improves energy utilization efficiency in small-scale photovoltaic systems.

The experimental results demonstrate that integrating real-time IoT monitoring with adaptive load control significantly improves the operational performance of small-scale photovoltaic systems. While conventional monitoring systems provide valuable data regarding voltage, current, and environmental parameters, they do not actively respond to changing operating conditions. In contrast, the proposed system combines monitoring and dynamic control, enabling more stable and efficient energy utilization.

The observed inverse relationship between panel temperature and output power confirms well-established photovoltaic behavior, where increased cell temperature reduces conversion efficiency. However, the results indicate that adaptive load control partially mitigates this negative effect by dynamically optimizing load conditions. This leads to improved voltage stability and reduced power fluctuation, particularly during rapid environmental changes such as cloud transitions or midday thermal peaks.

Compared to traditional small-scale solar installations that rely on fixed load configurations, the proposed adaptive mechanism reduces unnecessary stress on the photovoltaic module. The reduction of power fluctuation by up to 10–12% and efficiency improvement of approximately 6–9% demonstrate the practical benefits of implementing intelligent control strategies in decentralized energy systems.

From a technological perspective, the use of the ESP32 microcontroller provides a cost-effective yet powerful platform for integrating sensing, communication, and control functions. Its built-in Wi-Fi module simplifies system architecture and enables seamless cloud connectivity. This supports remote supervision, data logging, and potential integration with mobile applications or smart home platforms.

Furthermore, the proposed system contributes to the practical implementation of renewable energy optimization strategies. In small-scale installations, even moderate efficiency improvements can result in noticeable long-term energy savings. The scalability of the system makes it suitable not only for residential applications but also for rural electrification projects, educational laboratories, and small commercial setups.

Nevertheless, the current study focuses primarily on adaptive load control rather than full Maximum Power Point Tracking (MPPT) implementation. Although adaptive load adjustment improves stability, integrating advanced MPPT algorithms could further enhance energy harvesting efficiency. Additionally, long-term seasonal testing and broader environmental variability analysis would provide more comprehensive validation.

Overall, the findings confirm that the combination of IoT-based monitoring and adaptive control represents a practical and effective approach for improving the reliability, efficiency, and sustainability of small-scale solar energy systems.

This study presented the development and experimental validation of a real-time IoT-based monitoring and adaptive load control system for small-scale solar energy installations. The proposed system integrates sensing, data acquisition, wireless communication, and dynamic control within a compact and cost-effective architecture based on the ESP32 microcontroller.

Experimental results confirmed that continuous real-time monitoring enables accurate evaluation of photovoltaic system performance under varying environmental conditions. The implementation of adaptive load control significantly reduced power fluctuations and improved overall energy utilization efficiency. In particular, efficiency improvements of approximately 6–9% were observed compared to monitoring-only operation, demonstrating the practical benefit of integrating intelligent control mechanisms.

The developed solution is scalable and suitable for residential, rural, and decentralized solar energy applications. Its low power consumption and cloud connectivity make it appropriate for long-term deployment and remote supervision.

Overall, the findings highlight that combining IoT-based monitoring with adaptive control strategies represents an effective and practical approach to enhancing the reliability, efficiency, and sustainability of small-scale photovoltaic systems.

Future research will focus on integrating advanced Maximum Power Point Tracking (MPPT) algorithms, expanding long-term environmental testing, and incorporating predictive analytics techniques to further optimize system performance.

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