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ENERGY CONSUMPTION MONITORING AND ANOMALY DETECTION MODULE FOR A SMART AUTOMATIC IRRIGATION SYSTEM

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***Abstract*—*Modern smart automatic irrigation systems are widely used to improve water efficiency and crop productivity. However, most existing solutions primarily focus on soil moisture control and environmental conditions, while energy consumption behavior of irrigation equipment remains insufficiently analyzed. At the same time, abnormal energy consumption often serves as an early indicator of system malfunctions, water leakage, or inefficient operation of electromechanical components. This paper presents a module for monitoring energy consumption and detecting anomalies in a smart automatic irrigation system. The proposed solution is based on continuous measurement of electrical parameters and adaptive analysis of energy consumption patterns. The module enables early detection of abnormal operating conditions, improves energy efficiency, increases system reliability, and enhances operational autonomy. The developed approach can be integrated into existing irrigation infrastructures without significant hardware modifications and is suitable for private households and scalable smart farming systems.*

Keywords—Smart irrigation, energy consumption monitoring, anomaly detection, IoT, energy efficiency, smart farming, automated control.

I. INTRODUCTION

The rapid development of smart farming technologies is driven by global challenges such as climate change, increasing energy prices, and growing scarcity of freshwater resources. Agriculture remains one of the largest consumers of both water and energy, which makes efficiency and sustainability key priorities in modern irrigation systems.

Smart automatic irrigation systems have significantly improved water management by utilizing sensor data, weather forecasts, and automated control algorithms [6]. These systems reduce water waste and improve crop yields by delivering water precisely when and where it is needed [9]. However, the majority of current implementations focus on hydrological and environmental parameters, while the energy aspects of irrigation system operation are often overlooked [4].

Energy consumption plays a critical role in the overall efficiency and reliability of irrigation systems. Pumps, valves, and controllers operate under varying loads and environmental conditions, and changes in their energy consumption behavior may indicate emerging faults or inefficiencies [5]. Therefore, incorporating energy consumption monitoring into smart irrigation systems is essential for early fault detection, operational optimization, and long-term sustainability.

II. PROBLEM STATEMENT

Despite the widespread adoption of smart irrigation technologies, existing systems rarely include dedicated mechanisms for real-time energy consumption analysis. In many cases, energy data are either not collected at all or is used only for basic accounting purposes without deeper diagnostic interpretation.

This lack of energy-aware monitoring leads to several practical issues. Mechanical degradation of pumps, clogging of pipelines, or leakage in irrigation lines may remain undetected until significant performance degradation occurs. Additionally, inefficient energy usage increases operational costs and reduces system autonomy, particularly in systems powered by renewable energy sources.

Another challenge is the dynamic nature of irrigation systems. Operating conditions change depending on irrigation schedules, weather conditions, and seasonal variations. Static threshold-based approaches are often insufficient to capture such variability [3]. Therefore, there is a need for an adaptive solution capable of analyzing energy consumption patterns and identifying abnormal behavior in real time.

The problem addressed in this paper is the development of a specialized energy monitoring module that can be seamlessly integrated into smart irrigation systems and provide reliable anomaly detection under varying operating conditions.

To solve this problem it is necessary to develop the design of energy monitoring nodule, it`s architecture, hardware, software and anomaly detection mechanism.

III. System Architecture

The proposed energy monitoring module is designed according to the Internet of Things (IoT) paradigm and follows modular, multi-level architecture [2]. This approach ensures scalability, flexibility, and compatibility with existing smart irrigation infrastructures.

At the hardware level, the system includes an energy measurement unit (ESP32 microcontroller) capable of continuously measuring voltage, current, active power, and accumulated energy consumption [1]. A microcontroller unit (PZEM-004T) performs data acquisition, preliminary processing, and communication tasks. Wireless connectivity (Wi-Fi) enables data transmission to external interfaces without the need for wired infrastructure [7]. Simplified structure of proposed system is shown in Fig. 1.

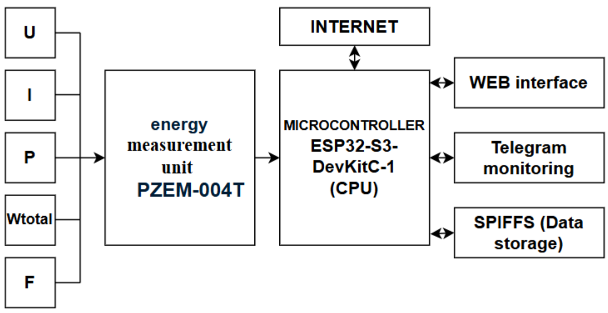

Fig. 1. Structural diagram of the energy consumption monitoring module

The module operates independently of the main irrigation control logic, which allows it to be added to existing systems without altering their core functionality. This design choice significantly reduces integration complexity and increases practical applicability.

At the system level, the architecture supports interaction with web-based interfaces and messaging services. This enables real-time monitoring, historical data analysis, and user notifications, forming a complete energy-aware monitoring solution.

IV. Energy Monitoring and Anomaly Detection Principle

The core functionality of the proposed module is based on continuous monitoring and analysis of energy consumption data. Under normal operating conditions, irrigation equipment exhibits characteristic energy usage patterns corresponding to specific operational modes, such as pump startup, steady-state operation, and shutdown.

The proposed anomaly detection mechanism is based on continuous monitoring of electrical parameters of the irrigation pump, including current *I*, active power *P*, and power factor *PF*. Detection combines threshold evaluation with dynamic variation analysis to identify both steady-state and transient abnormal conditions [8].

Three main anomaly types are implemented.

Dry-run condition (insufficient water intake) is characterized by reduced electrical load and decreased power factors:

$$I < I_{\text{dry}},\ P < P_{\text{dry}},\ PF < PF_{\min},$$

where $I_{\text{dry}}, P_{\text{dry}}$, and $PF_{\min}$ are experimentally defined thresholds.

Cavitation is identified through rapid parameter fluctuations within a time window:

$$\Delta P > DP_{\text{cav}},\quad \Delta I > DI_{\text{cav}},$$

where $\Delta P = |P_t - P_{t-1}|$ and $\Delta I = |I_t - I_{t-1}|$ and DP_{cav} is the threshold value of power variation, while DI_{cav} is the threshold value of current variation.

Overload condition is detected when electrical limits are exceeded:

$$I > I_{\max} \text{ or } P > P_{\max},$$

where I is the instantaneous current; P is the active power; $I_{\max}$ is the maximum permissible current, and $P_{\max}$ is the maximum permissible active power.

To reduce false positives, anomaly states are validated only if conditions persist over multiple consecutive measurement cycles. The system records the onset, termination, and cumulative duration of abnormal modes.

The detection logic is structured into an analytical layer (parameter filtering and gradient computation) and a signaling layer (decision-making and event generation for Web and Telegram interfaces), ensuring reliable and timely identification of unsafe operating regimes.

V. Software Implementation and User Interface

The software architecture of the module is implemented on the ESP32 platform and follows principles of modularity, functional separation, and real-time reliability.

The system is structured into independent functional components responsible for data acquisition, preprocessing, anomaly detection, logging, and communication. Electrical parameters (U, I, P, F, energy consumption) are acquired from the PZEM-004T sensor via UART at 1 Hz sampling rate. Raw measurements are validated for communication errors (NaN, timeout conditions) and processed using moving average filtering and standard deviation estimation to suppress transient fluctuations.

The anomaly detection module applies rule-based evaluation combining threshold comparison and dynamic variation analysis. Detection results are passed to the logging and notification subsystems.

Measured and derived parameters are stored in the SPIFFS file system in CSV format with cyclic size control. Both analytical data and anomaly events are logged for further diagnostics and performance assessment.

The embedded web server is implemented using ESPAsyncWebServer and AsyncTCP libraries, enabling non-blocking HTTP processing. The system provides:

- /data REST endpoint returning real-time measurements in JSON format;
- /download_log endpoint for CSV export of historical records;
- a single-page web interface stored in SPIFFS for real-time monitoring.

The web interface updates at 1 Hz without blocking the main control loop and displays raw, filtered, and statistical parameters along with anomaly state indicators.

In addition, a Telegram interface is implemented using UniversalTelegramBot over TLS-secured WiFiClientSecure communication. The module supports bidirectional interaction, status queries, and automatic push notifications upon anomaly detection. To prevent repeated alerts, edge-triggered logic is applied so that notifications are sent only when a new abnormal state occurs.

Push notifications are included for the following events:

- sensor_fault – sensor error or loss of communication. Criteria: receiving NaN values or exceeding SENSOR_ERROR_MAX limit;
- dry_run – pump operation without water. Criteria: $I < I_{\text{dry}}$ and $P < P_{\text{dry}}$;
- overload – electrical overload. Criteria: $I > I_{\max}$ or $P > P_{\max}$;
- cavitation – signs of cavitation or load instability. Criteria: exceeding thresholds for ΔI, ΔP or statistical deviations I_{stddev}, P_{stddev};
- powergrid – power supply voltage deviation from allowable range. Criteria: $U < V_{\min}$ or $U < V_{\max}$;
- low_pf – low power factor $PF < PF_{\min}$, that indicates the inefficient operation of pump.

Configuration parameters, including anomaly thresholds and logging intervals, are stored in an external configuration file (/config.ini), allowing system adaptation to different pump models without firmware modification.

The asynchronous architecture ensures stable operation of sensing, analysis, web interaction, and messaging tasks within the constrained computational environment of the ESP32.

This combination of visualization and automated alerts significantly enhances user experience and system usability.

VI. Practical Application and Result

The developed module was implemented and tested within a smart automatic irrigation system operating under conditions typical for a private household. The system included a water pump, irrigation pipelines, electromechanical valves, and a control unit.

During normal operation, the module successfully recorded stable energy consumption profiles corresponding to standard irrigation cycles. These profiles served as reference patterns for anomaly detection.

Example of user interface with the notification about detected anomaly is shown in Fig. 2

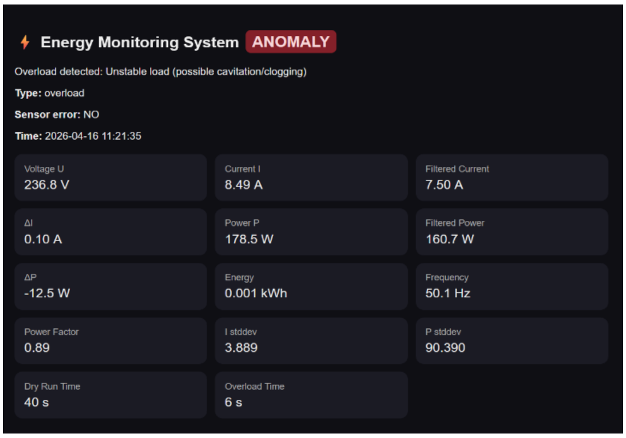

Fig. 2. User interface of energy consumption monitoring module

Several abnormal scenarios were evaluated, including increased load on the pump, partial obstruction of irrigation pipelines, and inefficient operation without effective water delivery. In all tested cases, the module detected deviations in energy consumption before visible degradation of irrigation performance occurred.

Detailed monitoring information, anomaly notifications and statistics are also reliably displayed via the Telegram bot control commands for which are shown in Fig. 3.

Example of systems current operation status monitoring data is shown in Fig. 4.

Example of anomalous operation statistics is shown in Fig. 5.

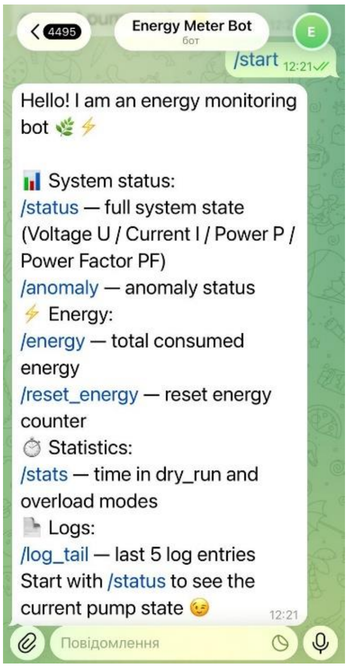

Fig. 3. List of control commands displayed by the Telegram bot

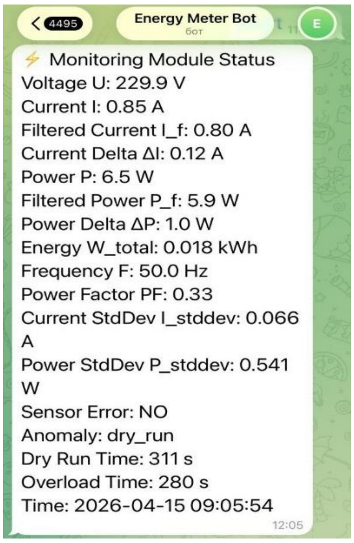

Fig. 4. System status information provided via the Telegram bot

Fig. 5. Anomalous operation statistics provided via the Telegram bot

In case of anomaly occurrence system also generated a push notification including the information about the type of an anomaly.

The results demonstrate that energy consumption monitoring provides valuable diagnostic information that complements traditional sensor-based irrigation control. The module enabled early detection of inefficient operating modes, reduced unnecessary energy usage, and improved overall system reliability.

VII. Conclusions

Proposed system is a comprehensive solution for monitoring energy consumption and detecting anomalies in smart automatic irrigation systems. The proposed module extends conventional irrigation control by incorporating energy-based diagnostics as a core system function.

The developed approach enables early detection of system malfunctions, improves energy efficiency, and enhances operational autonomy. Practical testing confirms that energy consumption analysis is an effective indicator of abnormal system behavior and can significantly improve the reliability of smart irrigation systems.

Integration of energy monitoring and anomaly detection represents an important step toward energy-aware smart farming technologies. The proposed solution can be applied to both small-scale private systems and larger agricultural infrastructures, contributing to sustainable and efficient resource management.

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М. П. Василенко, О. В. Загорна. Модуль моніторингу енергоспоживання і виявлення аномалій розумної системи автоматичного поливу

Моніторинг енергоспоживання є важливим елементом функціонування сучасних розумних систем автоматичного поливу, оскільки дозволяє оцінювати ефективність роботи насосного обладнання, електроклапанів та керуючих модулів. Більшість існуючих систем зрошення орієнтовані переважно на контроль вологості ґрунту та погодних умов, залишаючи енергетичні параметри поза межами оперативного аналізу. Це ускладнює своєчасне виявлення несправностей, таких як витоки води, засмічення трубопроводів або деградація виконавчих механізмів. У роботі запропоновано модуль моніторингу енергоспоживання розумної системи автоматичного поливу з функцією виявлення аномалій на основі аналізу електричних параметрів. Запропонований підхід дозволяє здійснювати безперервний контроль енергетичного стану системи, своєчасно виявляти нетипові режими роботи та підвищувати енергоефективність і надійність функціонування системи в цілому.

Ключові слова: розумне зрошення, моніторинг споживання енергії, виявлення аномалій, Інтернет речей, енергоефективність, розумне землеробство, автоматизоване управління.

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Кількість публікацій: більше 20 наукових робіт.
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