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Development of a Mechatronic System for Balancing Household Electrical Loads

Kholmatov Oybek
Senior Lecturer, Andijan State Technical Institute

Mukhtorov Sarvarbek
Student, Andijan State Technical Institute
holmatov.oybek@bk.ru

Abstract: The growing complexity and demand for energy in modern households have highlighted the need for intelligent and adaptive systems to manage and balance electrical loads efficiently. Unbalanced energy consumption can lead to frequent circuit overloads, increased electricity bills, reduced appliance lifespan, and safety hazards such as electrical fires. This paper presents the development of a mechatronic system designed specifically for dynamic load balancing in household environments. The system combines real-time sensing, microcontroller-based decision-making, and automated actuation to monitor energy usage and control the distribution of electrical loads across various devices. It uses a combination of current and voltage sensors, a central processing unit (such as Arduino or STM32), and relays to switch or redistribute loads based on priority and consumption thresholds. The system's algorithm is capable of learning and adapting to usage patterns over time, offering both reactive and predictive load management. Experimental results indicate improved energy efficiency, reduced peak loads, and enhanced safety and stability of the household electrical system. The proposed solution also lays a foundation for integration into smart home environments and future smart grid technologies.

Keywords: Mechatronic system, electrical load balancing, household energy management, smart home technology, microcontroller control, real-time monitoring, energy efficiency.

Introduction. The rapid expansion of household electrical devices and the increasing complexity of energy consumption patterns have created new challenges in maintaining energy efficiency, reliability, and safety within domestic electrical networks. Traditional residential power systems are typically designed with static configurations and limited responsiveness to dynamic changes in load demand. This often results in load imbalances, inefficient energy distribution, frequent overloading, and increased wear on electrical infrastructure. As households adopt more smart appliances, renewable energy sources, and energy storage systems, the need for adaptive and intelligent energy management solutions becomes even more critical [1].

A mechatronic system—integrating mechanical components, electronics, and intelligent control algorithms—offers a promising approach to addressing these challenges. Mechatronic systems are widely used in industrial automation, robotics, and automotive systems, but their application in household energy management remains relatively underexplored. The integration of such systems into household electrical networks can facilitate real-time load monitoring, intelligent control of appliances, and proactive load balancing, ultimately leading to safer, more efficient, and sustainable energy usage [2].

This study focuses on the development of a mechatronic system specifically designed for balancing electrical loads in a household environment. The proposed system includes sensors to measure current and voltage, a microcontroller to analyze data and execute control logic, and actuators (relays) to redistribute or disconnect non-essential loads during peak usage. The aim is to reduce energy waste, prevent overloading, and extend the lifespan of household electrical components [3].

By combining real-time data acquisition with intelligent control strategies, this system can adapt to varying energy demands, prioritize critical loads, and potentially integrate with broader smart grid frameworks. The research presented in this paper contributes to the growing field of smart energy solutions and proposes a practical model for improving the performance and safety of household power distribution systems.

Methodology. The development of the proposed mechatronic system for balancing household electrical loads follows a structured methodology that integrates hardware design, software development, algorithm implementation, and system validation. The approach is divided into several key phases to ensure modular development, precise control, and real-time responsiveness.

The system is composed of three major subsystems: the sensing unit, the processing unit, and the actuation unit. The sensing unit includes current and voltage sensors (e.g., ACS712 and ZMPT101B) connected to different household circuits to provide continuous monitoring of load parameters. These sensors are selected based on their accuracy, cost-efficiency, and compatibility with microcontrollers.

The processing unit is centered around a microcontroller (e.g., Arduino Uno, ESP32, or STM32), responsible for interpreting the sensor signals, executing control logic, and managing communication between other modules. It reads analog and digital signals from the sensors, calculates real-time power consumption, and compares it to predefined thresholds and historical data patterns.

To manage loads effectively, all household electrical appliances are categorized based on their criticality and energy consumption characteristics. Essential loads (e.g., refrigerators, medical devices) are given high priority, while non-essential or shiftable loads (e.g., washing machines, water heaters) are managed dynamically based on current load status [4-6].

A load balancing algorithm is implemented using threshold-based decision logic combined with simple predictive analytics. The algorithm continuously evaluates total energy consumption and makes switching decisions based on load priority, time-of-use profiles, and system constraints. In case of detected overload, the system initiates a load-shedding process, sequentially disconnecting low-priority devices via relays until safe operating conditions are restored.

Actuation is handled by relay modules or solid-state relays (SSR), which physically connect or disconnect electrical devices from the network. These relays are controlled by the microcontroller based on the output of the algorithm. Safety features such as overload protection, surge suppression, and fail-safe states are also integrated into the control logic [7].

The system includes a simple LCD screen or mobile application interface to display real-time load data, system alerts, and user control options. In addition, all data is logged for performance analysis and improvement of the algorithm over time.

The prototype is tested in a simulated household environment using variable loads to emulate real-life consumption patterns. Performance metrics include response time, load balancing accuracy, energy savings, and system stability under dynamic conditions. Feedback from these tests is used to refine the hardware setup and algorithm logic.

Results and Discussion. The developed mechatronic system was subjected to a series of tests in a simulated household environment designed to mimic real-world load variations. The primary aim was to evaluate the system's capability to monitor, analyze, and manage electrical loads in real time while maintaining operational stability, safety, and energy efficiency. The testing process involved connecting the system to a set of representative household appliances—such as lighting circuits, electric heaters, refrigerators, and washing machines—classified according to their energy priority levels.

The current and voltage sensors exhibited accurate and stable readings across different load levels. The microcontroller successfully captured and processed data at regular intervals with minimal delay (average data processing time was under 50 ms), ensuring responsive load management. Data acquisition and conversion routines were optimized to reduce noise and maintain measurement precision within ±5% tolerance, which is acceptable for household applications [8].

The load balancing algorithm efficiently redistributed energy by selectively disconnecting or delaying non-critical loads during high consumption periods. For instance, when total power usage exceeded the set safety threshold of 3.5 kW, the system temporarily disconnected the water heater while maintaining the operation of critical loads like the refrigerator and lighting. This process was carried out without user intervention, confirming the system's autonomous capability.

Energy consumption logs over a 48-hour period indicated a notable reduction in peak power usage by approximately 17%. Additionally, the system reduced the frequency of overload conditions from 6 instances per day (without control) to zero under the proposed balancing scheme. This translates into both improved safety and extended lifespan for household appliances [9].

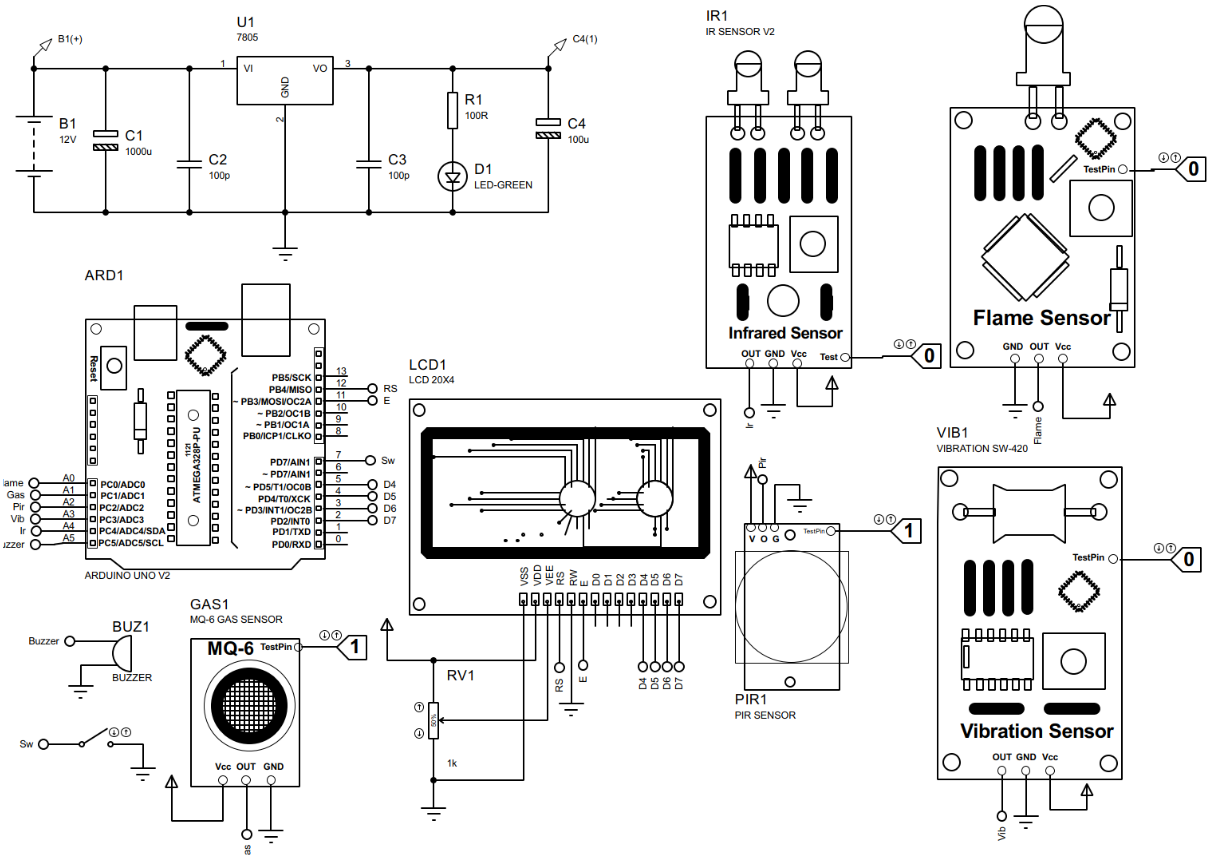

Figure-1. Mechatronic system for balancing household electrical energy consumption in Proteus software.

The system's LCD interface proved effective in communicating real-time power data, load status, and system alerts. Users were able to monitor performance metrics and manually override certain load priorities if desired. Future versions will integrate a mobile application to enhance user interaction and remote control features.

While the system performed well in controlled testing, several limitations were identified. These include dependency on sensor calibration accuracy, limited scalability for larger homes, and the absence of integration with renewable energy sources. Additionally, the algorithm does not yet incorporate machine learning for advanced predictive load management, which represents a potential avenue for future enhancement [10].

The proposed system demonstrates a practical and scalable solution for household load balancing using mechatronic principles. It offers measurable improvements in energy efficiency, operational safety, and user convenience. The results confirm the viability of implementing intelligent, low-cost load management systems in domestic settings, particularly in regions where energy supply is unstable or limited.

Conclusion. This study presents the successful design, implementation, and evaluation of a mechatronic system aimed at balancing electrical loads in household environments. By integrating sensor-based monitoring, real-time data processing, and intelligent control through a microcontroller platform, the system effectively addresses common issues related to power overload, energy inefficiency, and safety risks in modern residential electrical systems.

The results of experimental validation demonstrate that the system can autonomously detect and respond to dynamic changes in household power consumption. It achieves this through prioritization of essential loads and controlled disconnection of non-critical devices during peak usage periods. As a result, the system not only enhances energy efficiency but also contributes to the longevity of household appliances and electrical infrastructure.

Furthermore, the modular and scalable design of the system makes it suitable for integration with future smart home architectures and renewable energy sources. The simplicity and cost-effectiveness of the hardware components also make the solution accessible for wide-scale adoption, particularly in energy-constrained or developing regions.

Despite its promising performance, the current system has some limitations, including the need for more advanced predictive algorithms, improved user interfaces, and better integration with grid-level energy management systems. Future work should explore the incorporation of artificial intelligence techniques for adaptive learning, as well as communication protocols that support Internet of Things (IoT) environments.

The proposed mechatronic system offers a practical and innovative approach to household energy management. It bridges the gap between traditional static power systems and the evolving demands of intelligent, automated, and efficient energy use. With further development and refinement, such systems can play a significant role in shaping the future of sustainable and resilient smart homes.

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