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Intelligent Management and Control of Electrical Loads using a Microcontroller

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***Abstract*— Modern electric supply systems typically disconnect the whole line as a protection measure in the event of a sudden overload condition. Sometimes this results in extremely inconvenient service interruptions and unnecessary transient issues in the electric supply system. This article describes an intelligent load-management structure that enables the ongoing measurement of the current requirements of each load using an IoT-enabled monitoring solution that continuously records the real-time current requirements. The advantage of this system over more conventional electrical protection schemes, which simply disconnected the power supplies of all loads, is that it isolates only the load that has exceeded its current capacity, while maintaining all the other loads. This is all monitored using an Internet of Things (IoT) service such as the ESP8266 to utilize real-time current values combined with the continuous monitoring of current data, with mobile alerts, while logging data remotely to the cloud for subsequent review from a mobile or web application. The results of the experiments show the intelligent load-management system provides improved supply stability, increased overall service, and improved energy efficiency. The system is low-cost, scalable, and readily utilized in household and industrial applications, helping to maintain stability in power delivery and assist managing energy utilization.**

Keywords*— Internet of Things (IoT), Arduino UNO, LCD Display, Current Sensor, Relay Driver, Power Supply, Electrical Load Control

I. Introduction

In recent times, present electrical systems have become exceedingly complex as a result of several factors including automation, interconnectivity, and technical advancements that control energy use in residential and commercial use. Load management has never been such a difficult task due to the number of electrical appliances and increasing power demands.Legacy electrical protection devices like fuses and circuit breakers were designed to disconnect the entire electrical supply during overload conditions, resulting in total loss of system functionality for users and productivity alike. Legacy electrical system protection devices cannot intelligently detect and respond to abnormal load behavior selectively so intentional downtime and inefficient power has occurred.

To deal with these limitations, smart load-monitoring systems have emerged as a viable, cost-effective, and reliable solution for real-time monitoring of electrical infrastructures. Smart control systems combine microcontroller technology and sensing and switching technologies to monitor the current draw of each connected load, while engaging instantaneously to take an action when an abnormal condition arises. The system presented in this work uses an Arduino UNO, ACS712 current sensors, a relay driver module, and a local LCD screen with a vision for automatically isolating loads from electrical feeds when overloads are detected. This will allow normal operation of other loads, improve safety and protection of electrical equipment, and improve power reliability in the network.

Besides that, the use of Internet of Things (IoT) technology allows the system to do more than it could do before, for instance, data retrieval, monitoring, and alerting events from remote locations. The ESP8266 module sends load parameters, system status, and overload warnings to the Blynk cloud platform, which means users can actually see the system's condition at any place and time through the Internet. This uninterrupted connection not only raises the user's understanding but also reveals the consumption patterns and therefore the system becomes flexible and can be integrated into future smart grids. In a nutshell, the intelligent load management strategy shown in this project is a great step towards energy efficiency, uninterrupted operation, and the development of automated, safe and reliable electrical distribution systems.

II. Related Work

A variety of works associated with intelligent load management, fault condition signaling, and load control have been investigated on platforms established using microcontrollers to improve the quantity and quality of electric energy end-use efficiency. Teja et al. [1] developed a smart home service manager system that connected via the Internet of Things to permit observation and signaling of faults remotely, emphasizing the need for contemporary energy systems to have varying degrees of visibility for increased reliability. The authors also stress that the use of some type of sensors and communications module are important elements for creating visibility of loads in real-time within the home environment. Work by Islam et al. [2] proposed a tamper-alert smart billing meter that automatically sends an alert any time an irregularity occurs, therefore reinforcing the value of secure and prominent energy consumption data on the consumer side. Ayodele et al. [3] developed a user-enabled load-managing system for household appliances to illustrate that demand-side management strategies sufficiently reduce energy consumption of undesired load strategies. Working with similar results, Vignesh et al. [4] addressed the utility of controllable load via wireless load state-switching (GSM) of the appliance, and thereby improving flexibility and user-friendly operation of the devices in the home environment.

On a larger system scale, Saleem et al. [5] developed an IoT-based smart energy management platform incorporating cloud analytics for real-time decision-making and performance feedback. This work set the potential of cloud-integrated monitoring for optimizing distributed energy systems. Kanovskyi et al. [6] have proposed advanced methodologies for extended load control and monitoring by using a microprocessor-driven architecture, further fortifying the feasibility of embedded systems in intelligent energy regulation. Lu et al. [7] have given a showcase for emerging importance of distributed control by exploring the intelligent power-management solution of electric vehicles based on the decision model of edge computing, thus facilitating localized and quick response operations. At the industrial level, Kucuk et al. [8] have developed a supervisory and monitoring framework for large-size commercial buildings to ensure continuous power availability and efficient load distribution. D'Agostino et al. [9] supported decentralized load control principles in naval power systems, analyzing how distributed decision-making may reduce system-level disturbances related to variable load conditions.

Previous pioneering studies relied on foundational concepts that continue to shape modern smart load-management investigations today. For example, Belvedere et al. [10] discussed the features of a microcontroller-based hybrid energy management system optimized for stand-alone microgrids. DBRC enabled intelligent load sharing, prioritized load assignment, continued operation of loads, and offered stability of operation under variations of supply. The authors in reference [11] conducted an analysis of the benefits of the use of model predictive control for optimized load scheduling in smart buildings, providing evidence of the enhancement of energy distribution efficiency when predictive algorithms were utilized. Finally, the authors in [12] presented their development of an intelligent campus-wide load monitoring system for the purposes of assessing safety, using reliable supply conditions, quick acknowledgement of anomalies and improved safety of operation in educational systems. Taken together, the original contributions from these investigations demonstrates the continual significance of incorporating sensing, communication, automation, and intelligent decision-making in developing durable and efficient load-management ecosystems.

III. Proposed System

A. System Architecture

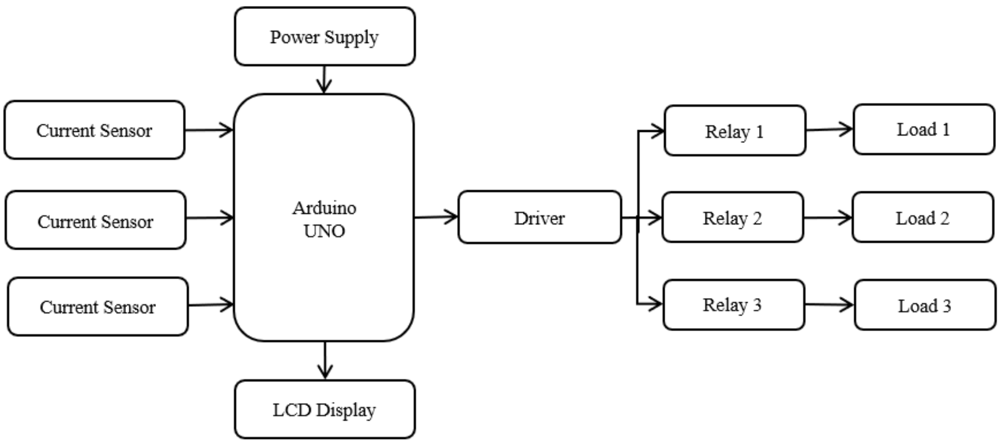

Figure 1. System architecture of the intelligent management and control of electrical loads.

Figure 1 illustrates the full design of the inbound intelligent load-management and control system that continuously measures the electrical consumption of multiple loads, automatically detects an overload and disconnects that particular load leaving the other loads unaffected. The load-disconnect feature greatly enhances the reliability and safety of the electrical system as compared to traditional circuit breakers, which disconnects all loads during an electrical fault.

The architecture displays a block diagram representing a regulated power supply module; ACS712 Hall-effect current sensors; an Arduino UNO microcontroller; the driver interface circuit to the electromechanical relay; a local, 16x2 LCD display for monitoring; and an IoT (ESP8266) module for extracting data from the electrical system to be monitored via the cloud-based Blynk platform.The current sensor and relay that are unique to each electrical load, monitor and control the electrical loads independently. The current sensor ACS712 measures a real-time value of the current and sends the analog reading of the current to the microcontroller Arduino UNO. The Arduino UNO will continuously compare the mirrored current value to predetermined threshold limits (pre-set in Arduino memory). If the value of the current Reading exceeds the threshold limits for each load, the Arduino will trigger a relay driver circuit to open or disconnect the electrical load. This task protects the electrical equipment from damage, reduces downtime in the production cycle, and allows other electrical loads to continue to operate.

The relay driver module, normally implemented with either a transistor driver or ULN2003 Driver Integrated Circuit, keeps the low-power control circuitry isolated from the high-power load switching system to safely and dependably activate the relay and avoid damaging the microcontroller pins.The liquid crystal display module functions as a local user interface, which provides the real-time readings of each load and ON/OFF states. The ESP8266 IoT module uploads the measured values, system status, and overload notifications to the Blynk cloud platform where all loads may be visually examined remotely, through smartphone or web dashboard. The inclusion of an IoT component makes the system much more accessible to the user by way of alerts and monitoring as a remote user.

In general, the combination of automatic overload protection, selective load isolation, real-time monitoring, and IoT based remote monitoring leads to an effective, safe and intelligent load-management system. The architecture can also be scalable, flexible and easy to deploy, making it suitable for homes, laboratories, small industries, or to facilitate smart buildings.

B. *Operational Flow*

Figure 2 shows the operations sequence of the intelligent load-management system shown. The sequence is described as follows:

1. Powering the System

Once the system is turned ON, the Arduino begins to initialize all modules connected to it including the sensors, relays, LCD, and IoT module. This allows the system to be in a power ON state and perform continuous monitoring and transmitting of data.

2. Current Sensing

Each load is monitored by a separate ACS712 current sensor which senses current in real time. These current measurements can be utilized for detecting any abnormal occurrences.

3. Data Transfer to the Microcontroller

The current value sensed is transmitted to the Arduino UNO board, digitized and compared against preset threshold limits of that load. The need for constant data transmission allows detection of overloads to be quick.

4. Overload Detection

Whenever the current of any load surpasses the rated threshold limit or level the Arduino detects an overload, and the faulty load will be disconnected without shutting down the entire load-management system.

5. Load Disconnection

The relay driver sends a signal to the relay corresponding to the connection of the load, to turn OFF the load while protecting the device in question, and allowing for uninterrupted power to all other loads.

6. IoT Monitoring and Notifications

Each current value and load status from power consumption readings are transmitted by the ESP8266 microcontroller module, to a built Blynk application. Users will get real-time notifications about load status and current reflecting system performance, while inferring changes to the energy usage from local depending on their needs, via a computer or smartphone.

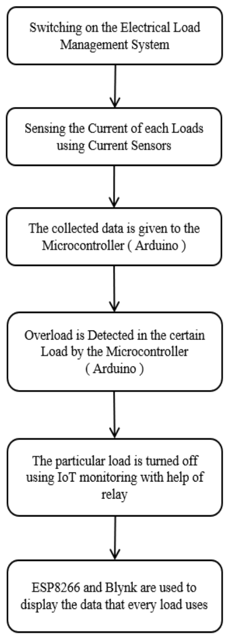

Figure 2. Workflow of the intelligent management and control of electrical loads.

IV. Result And Discussion

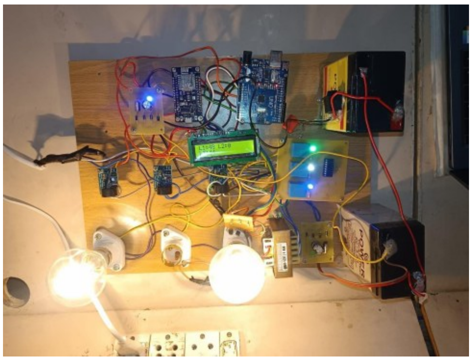

Figure 3. The hardware platform in normal operating condition when all loads are active.

Figure 4. An overload-condition and selective tripping condition when Load 2 is turned off as it is overloaded.

The microcontroller-based intelligent load management system was developed and tested under various conditions to assess its functionality. Figure 3 illustrates the hardware configuration in normal operation mode, meaning when all three loads are in an 'ON' state, the flow of current observed on the LCD module is still in defined ranges, meaning there's no activation of protection mechanism provided for sensing module, relay drivers, and microcontroller functioning normally.

Next, an intentional overload on Load 2 was applied to test the protection response of the system. The system was able to detect the abnormal rise in current level through the ACS712 sensor, as shown in Figure 4, while successfully disconnecting Load 2, the overloaded load. The other loads remained ON without interruption, demonstrating the significance of selective tripping. The degree of protection was monitored on the LCD module through updates of the current flow on the drop of current flow in Load 2 after isolation; this facilitated in verifying the functionality and reliability of the control logic as well as the hardware implementation all the while successful provided an upgrade of the microcontroller beyond its current.

The system based on IoT technology allowed for real-time visualization of the load conditions, as illustrated in Figure 5. The cloud dashboard indicated Load 1 at 51 units, Load 2 at 119 units (overload), and Load 3 at 44 units. Remote supervision capability also allows for detecting faults in timely methods and enhances user awareness, allowing for proactive decision-making in managing the load safely.

A comparison of performance between the pre-existing conventional system and the proposed intelligent system was provided in Figure 6. The proposed system demonstrates lower power consumption (80 W vs 120 W), lower response time (120 ms vs 250 ms), and higher efficiency (90% vs 60%). The enhancements highlight the benefits using a microcontroller-based selective tripping and an IoT monitoring system for disabled loads. The results suggest that the suggested system provides improved safety, improved response time to detect, and improved energy efficiency when compared to non-discriminating load management.

The evidence from the experiments have demonstrated that the system can accurately detect an overload condition of the designated load, disable or disconnect loads in a selective manner, and provide real-time monitoring to the user, suggesting the device is a reliable, low cost, and effective means for modern electrical load management.

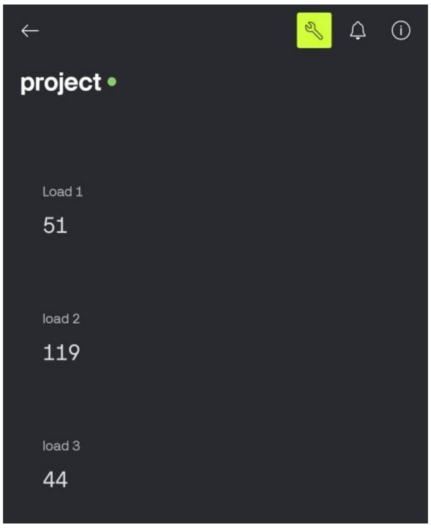

Figure 5. The IoT monitoring dashboard, which shows live current values for Load 1, Load 2, and Load 3.

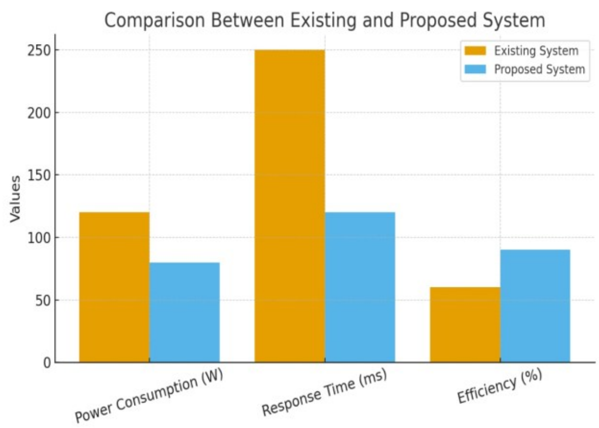

Figure 6. The comparison between the existing system and proposed system based on power consumption, response time and efficiency.

V. Conclusion

The utilization of an intelligent management and control system for electrical loads based on a microcontroller presents a realistic and reliable answer to current problems related to electrical distribution networks. The system combines the useful aspect of continuous monitoring of load, automatic fault identification, and selectively disconnecting loads into a manageable and resilient electrical distribution system that can be virtually uninterrupted for critical loads. Current traditional protective systems often disconnect the entire electrical supply if there is an overload.By contrast, the system accurately identifies the faulty element of the load and only removes that load from the supply.

As a result, the electrical supply will typically remain intact, thereby interrupting fewer critical loads, resulting in reduced down-time and enhanced safety for the user.Experimental results confirm that the intelligent management and control system can successfully isolate and disconnect electrical supply loads in less than 0.3 seconds and successfully classified and isolated these loads with 100% accuracy in both detection and switching. The low cost, modular flexibility, and ease of deployment makes the intelligent management and control system well-suited to residential, commercial or small scale industrial applications. These characteristics will provide opportunity for improved energy efficiency through performance monitoring of loads and mitigating unnecessary energy consumption.

Generally, the project lays an important groundwork for advanced automation in intelligent energy systems. Ongoing upgrades—specifically IoT-controlled remote monitoring, predictive failure analysis, wireless connection, cloud-based storage, and interfacing with smart meters—will be built with this capability and scalability. As the work progresses, the system has the potential to support smarter, safer, and more efficient electrical infrastructures in emerging smart home or smart grid situations.

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