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Design and construction of an Arduino-based load-shedding management system for improving electricity consumption in a medium-sized creative office building

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Abstract— Standalone energy generation is revolutionizing electricity production and consumption by offering decentralized and sustainable options, benefiting communities, enhancing resilience, and reducing dependence on traditional power grids. Nevertheless, standalone electricity systems can face overloading issues when demand varies or exceeds capacity, necessitating careful control and adaptable solutions. The scalability of standalone electricity systems is limited by infrastructure, technology, and cost, hindering easy capacity expansion to accommodate higher loads. This paper explores the feasibility of managing load shedding in an office building with a standalone energy source, assessing its impact on optimizing electricity consumption and contributing to operational efficiency, sustainability, and resilience. A hardware prototype has been developed for a programmable interface designed to manage various loads from the distribution board automatically and in a controlled manner. This includes controlling lighting, heating, cooling, security devices, and essential office gadgets. The system is implemented and validated through experiments utilizing the Arduino Mega control board. Operators can input load-shedding times flexibly using a 4x4 matrix keypad synchronized with the real-time clock (RTC). The microcontroller then instructs the relay to shed the specified load, displaying the shedding time on the LCD. The results indicate that the programmable interface exhibits a high dynamic response speed, highlighting its effectiveness and flexibility in load-shedding management. Comparing the cost of building the device with the long-term cost of overloading a standalone electricity generator, considering accelerated wear and tear, increased maintenance expenses, reduced operational lifespan, potential premature equipment failure, and overall decreased reliability, underscores the high-cost efficiency of adopting this device in office buildings. Additionally, implementing the system in an office building with an energy consumption of 23 MWh per annum resulted in a discernible annual energy saving of 9.86MWh by shedding off unnecessary loads at estimated timings.

Keywords— *Electricity demand, load shedding, office management, and programmable interface*

Journal of Digital Food, Energy & Water Systems [JD-FEWS]

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1 Introduction

In contemporary office environments, the energy demand is dynamic and influenced by factors such as workforce activities, technology usage, and the diverse functions within the workspace [1]. As the necessity for sustainability gains prominence, organizations increasingly recognize the significance of optimizing energy consumption to reduce operational costs [2], [3]. This research addresses the challenges of medium-sized creative office buildings, whose energy needs are often intricate due to integrating various equipment and technologies essential for creative workflow [4]. Traditional approaches to energy management, like static scheduling, manual control systems, rule-based systems, and non-integrated systems, may fall short of accommodating the variable requirements of such dynamic settings, leading to suboptimal energy utilization [5].

Furthermore, the utilization of independent energy generation, sourced either from renewable (for instance, solar panels, wind turbines) or non-renewable (for instance, diesel generators, batteries) means, within office buildings presents decentralized and environmentally friendly alternatives to traditional grid-dependent systems. [6]–[8]. However, effective load-shedding management becomes paramount to fully realizing the benefits of standalone energy [9], [10]. The rationale for this study is to develop and implement a load-shedding system based on Arduino technology, specifically customized to meet the distinctive requirements of a medium-sized creative office. Such a system holds the potential to enhance energy efficiency and contribute to the overall sustainability and resilience of the office environment. The landscape of energy generation and consumption is transforming, with standalone energy generation emerging as a pivotal player in reshaping the traditional paradigms of electricity production [11], [12]. The conventional reliance on centralized power grids is being complemented by standalone systems and, in some cases, supplanted.

While standalone energy generation systems bring many benefits, the challenge of effectively managing these systems to prevent overloading becomes paramount [10]. Variability in demand and unforeseen peaks can strain the capacity of standalone electricity systems, necessitating the development of sophisticated load management solutions [13], [14]. Addressing this challenge is crucial for ensuring the reliability and longevity of these systems, as well as for unlocking their full potential in diverse settings.

This research delves into the critical aspect of load-shedding management within a medium-sized creative office building powered by a standalone energy source. As organizations increasingly recognize the importance of sustainable practices, the need for efficient energy utilization becomes imperative. The proposed solution involves designing and implementing a programmable interface utilizing the Arduino Mega control board to shed loads at strategic times systematically. The loads encompass various components crucial to the office environment, including lighting, cooling and heating systems, security devices, essentials, and office gadgets. Through this study, we aim to assess the feasibility and effectiveness of the implemented load-shedding management system. The hardware prototype, incorporating a 4x4 matrix keypad for flexible input, real-time clock synchronization, and a relay-controlled shedding mechanism, is subjected to rigorous experimental validation. The research examines the technical aspects of the programmable interface and explores its impact on optimizing electricity consumption,

JDFEWS 4 (2): 141 - 158, 2023
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contributing to operational efficiency, sustainability, and resilience within the office building setting. Furthermore, the study extends its evaluation to the economic realm by comparing the upfront cost of building and implementing the load-shedding system with the potential long-term costs associated with overloading a standalone electricity generator. Considerations include accelerated wear and tear on equipment, increased maintenance expenses, reduced operational lifespan, the risk of premature equipment failure, and a decline in overall system reliability.

This manuscript is structured as follows: Section 2 provides an overview of the relevant literature related to the study. Section 3 outlines our methodology for office load management, control, and circuit design. Section 4 delves into the outcomes of our experimental endeavors. Finally, in Section 5, we offer conclusions based on our research findings and propose potential avenues for future exploration.

2 Related work

The research on load shedding management of standalone energy in buildings is driven by the essential need to optimize performance, enhance efficiency, and ensure the reliability of standalone energy sources with a focus on extending component lifespan, preventing overloading, improving electricity supply quality, and minimizing environmental impact. Therefore, using the programmable interface to manage load switching is an important strategy for dealing with building energy management difficulties. Numerous investigations have proposed and examined diverse load-shedding management systems for standalone generators based on Arduino technology. In a study by [15], a conceptual model for an Android application was introduced, serving a smart microgrid power pool monitoring and control scheme. The Arduino IDE was employed to develop, monitor, and control the operational algorithm of the system. The findings demonstrated that Android facilitates remote soft-touch human-machine interfaces, enhancing optimal energy operation. According to the findings, future research endeavors could focus on extending a similar scheme to encompass up to 10 communities. Furthermore, a revolutionary algorithm was developed to incorporate current solar photovoltaic and utility supply charging systems [16]. An Arduino microcontroller is equipped with an algorithm that detects the voltage of the battery and then uses that information to manage the availability of the utility grid supply by connecting or disconnecting a relay. This allows the battery to be charged continuously. The design was customized to tackle the issues of irregular power supply that commonly arise in Indian circumstances, leading to planned and unplanned load shedding. In another study [17], an Arduino microcontroller, coupled with a switching circuit, was employed to implement a load-shedding plan in four settlements of a laboratory-scale urban setting designed for teaching and research purposes. The power distribution Company approved the switching plan, ensuring optimal usage of the available 7.5MW against a 10MW power demand. [18] introduced an intelligent meter capable of monitoring usage patterns, reducing load during peak hours, and cutting electricity costs by 25-30%. Linked to a GSM module, the meter receives updated energy consumption units via Arduino Uno and controls appliances on/off using the Internet of Things (IoT) through switching mechanisms. Furthermore, [19] recommended a residential load-shedding method for demand-side load management in a real system under a time-of-use tariff. Demand-side load management is

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

achieved without changing the electricity meter using an Arduino microcontroller system, incorporating the developed load-shedding algorithm. The microcontroller also generates signals the relay system uses to control the lines at the output of the electricity meter. [20] conducted an intelligent wiring design for domestic house layouts, utilizing solar panels for load shedding. An intelligent Arduino system controlled the loads, resulting in a prototype with high safety, reliability, and automation performance. Additionally, [21] designed a model providing a stable and efficient real-time load-shedding technique. Interfacing with Arduino Uno, the real-time clock DS1302 replaces manual ON/OFF operations, overcoming associated challenges.

With its ATmega2560 microcontroller, the Arduino Mega has been effectively utilized in various load-shedding management systems due to its robust processing power and extensive I/O capabilities. The Arduino Mega's many digital and analog pins have proven crucial in energy management. [22] proposed a lightweight smart demand response management scheme for direct load control in a residential grid. Verified through simulation and deployed on a test bed, this algorithm assumes static priorities for every house and its appliances, with Arduino Mega as the decision-making unit.

Furthermore, the Arduino Mega's large memory capacity allows for storing and processing substantial amounts of data, a feature essential in load-shedding systems. This was exemplified in a project by [23], where an infrared radiation sensor and light-dependent resistors (LDR) were used to signal the Arduino Mega to control energy usage. The Arduino Mega's multiple UART interfaces enable it to communicate with various devices, such as energy meters and GSM modules. This was demonstrated in a study by [24], where the Arduino Mega was used to send SMS alerts during load-shedding events. These practical implementations underscore the suitability of the Arduino Mega in designing and constructing an efficient load-shedding management system for improving electricity consumption in medium-sized creative office buildings. The Arduino Mega's capabilities align well with the requirements of such a system, making it a preferred choice over other Arduino boards.

These studies demonstrate the feasibility and effectiveness of using Arduino-based load-shedding management systems for standalone or microgrids and provide useful insights and references for designing and constructing a similar system for a standalone office building. However, some challenges and limitations need to be addressed, such as the scalability, robustness, and user-friendliness of the Arduino-based load-shedding management system. Therefore, further research and development are needed to improve the performance and functionality of the Arduino-based load-shedding management system for a standalone office building and to evaluate its impact on its electricity consumption and energy efficiency.

3 Methodology

The design procedure followed in implementing the load-shedding management system with a programmable interface was segmented into two integral parts: hardware design and software design. The automatic load shedding system is designed for a single phase four load distribution box. The design allows for expansion to multiple loads up to ten, depending on the building's power distribution system. In this project, four loads are connected,

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

operating through a microcontroller using an AC contactor switch and 4x4 relay module board. Since power system relays are used to trip the circuit at any fault or disturbance, power relays are used to shed a particular load at any time as set. The load-shedding management system incorporates a 5V relay with a coil draw of 30mA, demonstrating an energy-efficient design. The relay's switching capacity of 230V ensures it can effectively control electrical loads within the medium-sized creative office building. In conjunction with the relay, the MCCB (Molded Case Circuit Breaker) has a rated voltage of 230V, 30A unit with short circuit breaking capacity to ensure safe and efficient load management in the designed system. The relay receives the command from the microcontroller.

Input load shedding time is provided through input 4x4 matrix keypad. Upon synchronizing the real-time clock (RTC) with the specified load-shedding time, the microcontroller issues a command to the relay, removing the designated load from the system. Subsequently, the shed time is presented on the LCD (16x2 character LCD module with an HD44780-compatible controller). The DS3231 RTC module selected for load-shedding management research with Arduino Mega features exceptional accuracy with a deviation of only a few seconds per month. Its low power consumption is within the range of 2.0μA, contributing to energy efficiency. The integrated temperature compensation ensures reliable timekeeping, and the module incorporates a temperature sensor with a measurement range of -40 °C to +85°C. These specifications justify its selection, offering precise timekeeping, energy efficiency, and additional temperature-sensing capabilities to enhance the overall effectiveness of the load-shedding management system.

The internal program runs at power up. After initial startup, the controller will revert the relay module to the load shedding state, turning connected loads OFF for a set delay period. After the delay times out, the program will look at the default scheduling algorithm developed and shown in Tables 1 and 2. The program will then repeat the process of restoring and removing load based on the schedule.

Table 1. Load shedding schedule between 00:00 to 11:00

Load	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**
Load 1	Off	Off	Off	Off	Off	Off	On	On	On	On	On	On
Load 2	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	On
Load 3	On	On	On	On	On	On	On	On	On	On	On	On
Load 4	Off	Off	Off	Off	Off	Off	On	On	On	On	On	On

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

Table 2. Load shedding schedule between 12:00 to 23:00

Load	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Load 1	On	On	On	On	On	On	On	Off	Off	Off	Off	Off
Load 2	On	On	On	On	On	On	Off	Off	Off	Off	Off	Off
Load 3	On	On	On	On	On	On	On	On	On	On	On	On
Load 4	On	On	On	On	On	On	On	Off	Off	Off	Off	Off

Load 1 – lighting, load 2- cooling and heating, load 3- security devices and essentials, load 4 – office gadgets.

The proposed system was simulated to validate its functionality through testing, while the simulation model was implemented using Proteus simulation software. The simulation was conducted to verify the efficacy of the proposed system.

3.1 Design approach

The initial design approach involved researching and assessing the feasibility of the load-shedding controller. Another crucial step was understanding the fundamental principles governing the distribution box and comprehending the intricacies of the building's wiring. Determining the load capacity of the device that would be controlled and classifying these loads into different categories was undertaken and presented in section 4. Figure 1 presents the flow diagram of the hardware design. The subsequent steps included selecting appropriate components and parts for constructing the load-shedding distribution box and exploring datasheets to understand the interactions between various components.

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

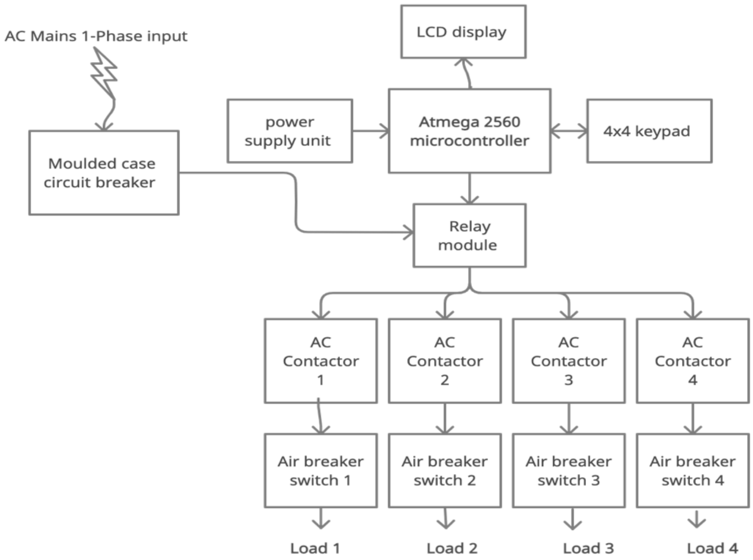

Fig. 1. Flow diagram of the hardware design

The power supply connection for the system was meticulously designed to ensure reliability and stability. It comprises a series of components: a 220V/12V step-down transformer, a full-wave bridge rectifier, a 1000uF electrolytic capacitor filter, a 7805 voltage regulator, and a 1A fast-blow fuse. The transformer reduces mains voltage to 12V AC, subsequently converted to 12V DC by the rectifier. The filter minimizes ripples and noise, while the regulator maintains a constant 5V DC output, protecting against input voltage variations. A fast-blow fuse safeguards the system from overcurrent or short-circuit incidents. This regulated power is channeled to the Arduino Mega and the relay through suitable connectors and wires. The Arduino Mega interfaces with a 2N2222 NPN transistor, amplifying a low-current signal from an Arduino pin to control the Single Pole Single Throw (SPST) relay efficiently. To protect the transistor from back-EMF generated during relay deactivation, a 1N4148 diode is integrated with the relay coil, ensuring the overall reliability and longevity of the load-shedding management system's switching mechanism.

3.2 System process

The Arduino Mega development board incorporates ATmega2560 microcontrollers, which were programmed using C++. The Arduino Mega's ATmega2560 microcontroller, with its high number of I/O pins and large memory, is ideal for managing complex systems [25]. Its robust processing power will ensure efficient electricity consumption management in medium-sized creative office buildings. The Arduino project offers an integrated development environment (IDE) for compiling and uploading programs to the microcontroller via the Arduino development board. The step-by-step processes of the system are illustrated in Figure 2 through a flow chart. The project's code is included in the appendix of this article.

The hardware construction phase entailed building and connecting the components using the circuit diagram in Figure 3. The firmware code for the microcontroller responsible for load shedding was written, and the developed algorithm was implemented for load shedding management.

Journal of Digital Food, Energy & Water Systems [JD-FEWS]

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

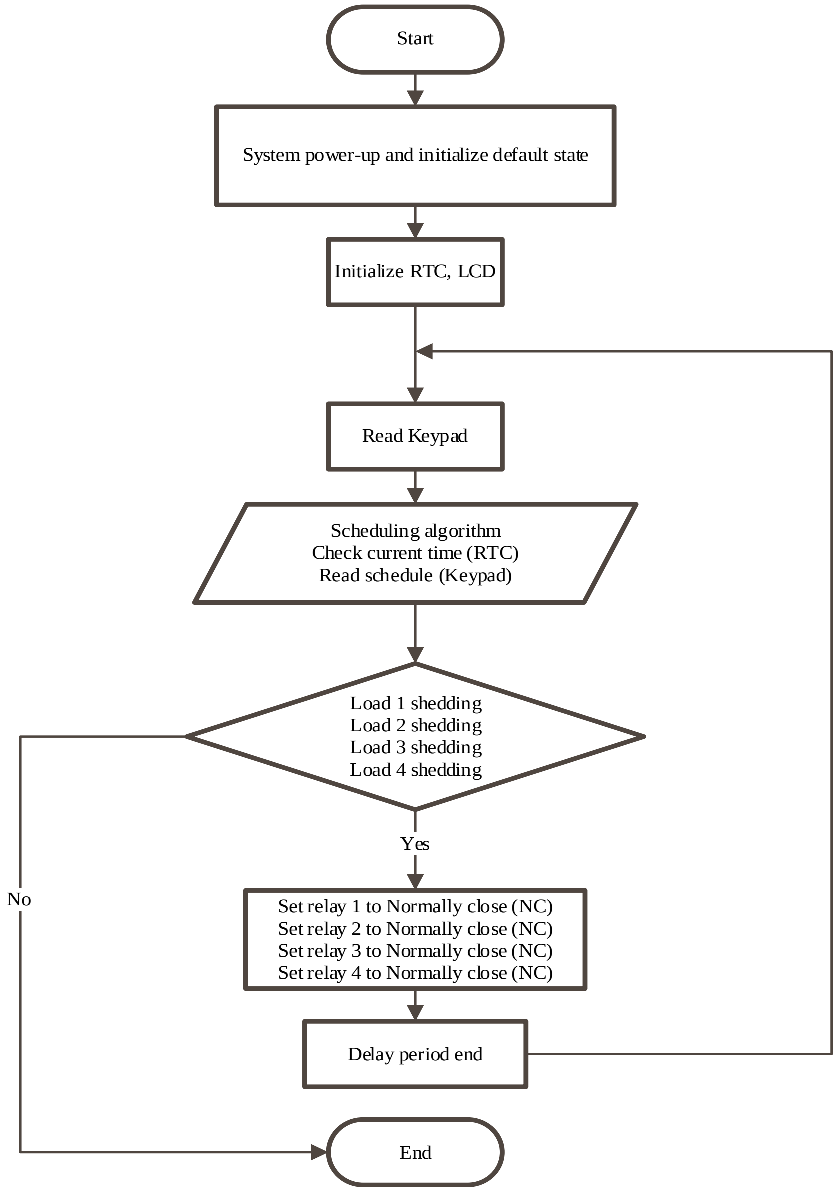

Fig. 2. Flow chart of the step-by-step processes of the system

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

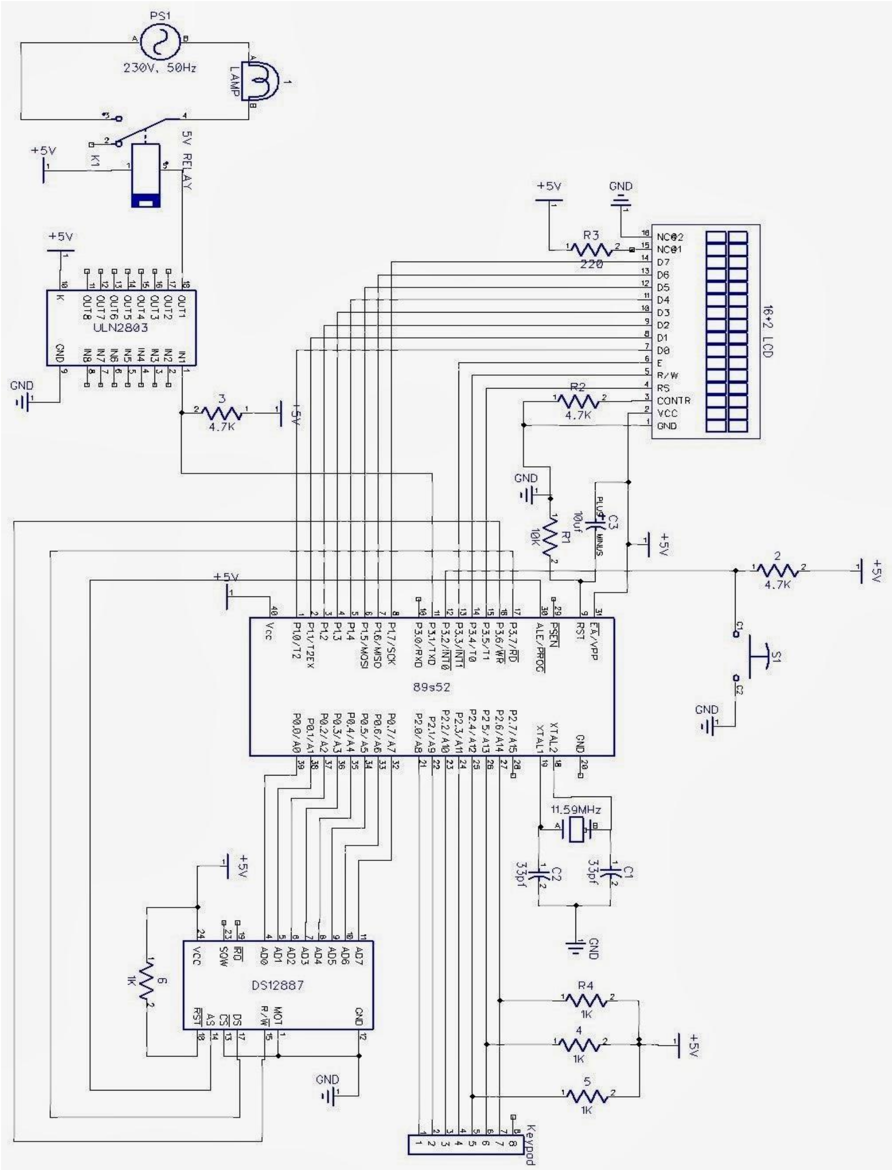

Fig. 3. Circuit diagram of the programmable interface in proteus software

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

4 Results and Discussion

4.1 Project prototype

The connection process was initialized by identifying the necessary components and the connection points. The components were verified for integrity through resistance checks, utilizing a multimeter before connection. The testing phase was conducted to validate the functionality of the designed system. The initial testing of the project design was implemented on a breadboard. The soldering procedure was carried out to attach the components to a vero board.

A case was then designed to house the entire circuit, encompassing the core components and external peripherals such as indicators, LCD, keypad, and switch. This comprehensive encapsulation ensured the protection of the internal circuitry and facilitated efficient operational interplay between the integrated components. The casing design considered the spatial arrangement and optimal positioning of each element, promoting seamless functionality within the confined space and contributing to the overall robustness of the constructed system.

Following the construction of the circuit and the casing, the assembly focused on the precise arrangement and integration of the various sections within the designated casing. This process involved the interconnection of peripheral devices, strategically linking each element to optimize operational efficiency. The assembly configurations depicted in Figure 4 are designed to optimize interconnectivity and operational efficiency within the assembled system.

Journal of Digital Food, Energy & Water Systems [JD-FEWS]

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

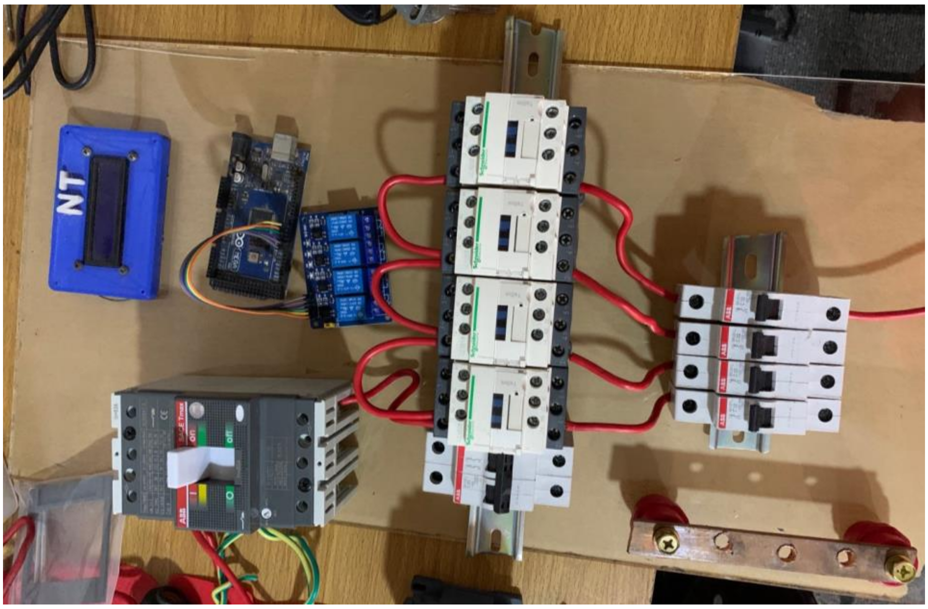

Fig. 4. Proposed configurations of parts

4.2 Prototype test

The post-construction results analysis was done following comprehensive troubleshooting to indicate a commendable system performance, showcasing its proficient responsiveness to operational demands. An energy consumption assessment was conducted to quantify the consequential impact of the project on a creative office building with a load of 23 MW. To find the energy consumption per hour of the medium-sized creative office building, we can use the equation (1).

$$Energy\ Consumption\ per\ Hour\ = \frac{Total\ Energy\ Consumption}{Total\ Number\ of\ Hours} \tag{1}$$

Given the total energy consumption as 23MWh per annum, and the total number of hours is 10 hours daily for 365 days.

$$Energy\ Consumption\ per\ Hour\ = \frac{23MWh}{10\ hours\ per\ day\ \times 365\ days} \tag{2}$$

$$= \frac{23}{3650} MWh/h$$

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

$$= 0.0063MWh/h$$

Therefore, the energy consumption per hour is approximately 0.0063 MWh/h.
Equation (3) was used to calculate the new total annual energy consumption when the usage hours were reduced from 10 to 6 hours per day.

$$New\ Total\ Annual\ Energy\ Consumption = Energy\ Consumption\ per\ Hour \times New\ Total\ Number\ of\ Hours \times Days\ per\ Year \quad (3)$$

$$New\ Total\ Annual\ Energy\ Consumption\ (6\ hours\ per\ day) = 0.0063MWh \times 6 \times 365 \quad (4)$$

$$= 13.14MWh$$

Therefore, when the energy usage was reduced from 10 hours to 6 hours per day, the new total annual energy consumption was approximately 13.14MWh.

The shift in daily energy usage from 10 to 6 hours notably influences the overall annual energy consumption. Initially, with a daily usage of 10 hours, the yearly energy consumption amounted to 23 MWh, indicating a substantial demand for power. However, by reducing usage duration to 6 hours per day, the annual energy consumption experienced a significant decrease, reaching approximately 13.14MWh. This considerable disparity underscores the efficiency gains resulting from a more mindful and restrained approach to energy consumption. The adjustment reduces energy costs and aligns with sustainable practices, emphasizing the importance of optimizing energy use for economic and environmental considerations. The reduction in annual energy consumption, achieved by implementing the proposed construction in an office building, amounts to approximately 9.86MWh.

Following Nigeria's National Electric Power Policy, the tariff established by distribution companies for customers was assessed at 51.11 Naira per kWh [26].

To calculate the cost for 9.86 MWh at a rate of 51.11 Naira per kWh, equation (5) was used.

$$Cost = Energy\ Consumption \times Rate \quad (5)$$

Where:
Energy Consumption = 9.86 MWh
Rate = 51.11 Naira per kWh

$$Cost = 9.86MWh \times 51.11\ Naira\ per\ kWh \quad (6)$$

$$Energy\ Consumption\ in\ kWh = 9.86MWh \times 1000kWh/MWh \quad (7)$$

$$Energy\ Consumption\ in\ kWh = 9860kWh$$

$$Cost = 9860kWh \times 51.11Naira\ per\ kWh$$

$$Cost = 504{,}004.60\ Naira$$

Therefore, the cost saved for 9.86 MWh at a rate of 51.11 Naira per kWh amounts to approximately 504,004.60 Naira. This analysis underscores the system's efficacy in optimizing electricity consumption. The findings contribute to the broader discourse on sustainable energy management strategies in office environments.

4.3 Cost analysis

Furthermore, the complete analysis of the financial cost associated with procuring components and materials for the project's construction is systematically detailed in Table 3, showcasing the comprehensive breakdown of costs in Nigeria Naira.

Table 3. Cost expenditure for building the device

S/no.	Items	Description	Cost (Naira #)
1	Arduino Mega board	MEGA R3 Board ATmega 2560	#34,587.74
2	Keypad	4 x 4 Matrix Array 16 Key Membrane Switch Keypad Keyboard Compatible	#8,721.74
3	LCD Display	LCD Display Module DC 5V 16x2 Character	#10,303.46
4	Wires	Multicolored Dupont Wire 40pin Male to Female, 40pin Male to Male, 40pin	#5,542.64
5	Earthing rod	Brass Grounding Rod with 40ft Wire, Earthing Rod Great to Use with Grounding	#21,057.86
6	AC Contactors	40 Amp contactor 240V coil HVAC Contactor	#13,721.06
7	Air Breaker Switch	Low-Voltage Miniature Air Circuit Breaker Circuit Breaker	#12,139.29
8	Real-Time Clock Module	RTC Breakout Module DS3231 Board 3.3V 5V	#10,303.46

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

9	Relay Module	4 Channel 5V Relay Module OPTO-Isolated Support High and Low Level Trigger	#5,868.52
10	Power supply kit	Component Power Supply Module Assorted Kit for Arduino Power Supply Kit	#7,935.54
11	Miscellaneous		#11,917.95
		Total	#142,099.26

This detailed breakdown reflects a total expenditure of #142,099.26 to procure essential components. The presentation of a comprehensive cost breakdown in this research is essential to transparently delineate the allocation of resources, ensure reproducibility, and facilitate informed decision-making for future endeavors within the field. Also, the presented cost analysis serves as a valuable reference for researchers and practitioners in the field, contributing to the broader discourse on the economic considerations associated with implementing advanced technological systems.

4.4 Limitations of the research and future works

This research has some limitations that need to be acknowledged and addressed in future studies. The hardware prototype was tested in a simulated office environment, not in a real office building with a standalone energy source. Therefore, the actual performance and reliability of the device may vary depending on the environmental conditions, the quality of the energy source, and the user behavior. The operators input the load-shedding times manually using a keypad, which may introduce human errors and inconsistencies. A more automated and intelligent method of determining the optimal load-shedding times based on the energy demand and supply could improve the accuracy and efficiency of the system. The energy saving of 9.86MWh per year was calculated based on the average energy consumption of an office building in Ikeja, Lagos, Nigeria, which may not be representative of other regions or countries.

Moreover, the energy saving may change depending on the season, the weather, and the occupancy of the office building. The cost-benefit analysis of the device was based on some assumptions and estimates, which may not reflect the actual costs and benefits of adopting the device in different scenarios. A more comprehensive and realistic analysis of the economic and environmental impacts of the device is needed to justify its feasibility and attractiveness.

Considering the limitations identified in this research and the corresponding findings, several promising directions exist for future investigations. Conducting field experiments in genuine office buildings equipped with standalone energy sources would allow the results to be compared with those obtained from simulated experiments. This approach not only ensures more valid and reliable data on the performance and reliability of the device

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

but also sheds light on potential challenges and opportunities in its practical implementation. Developing a more advanced and adaptive algorithm for determining optimal load-shedding times is crucial. This should consider energy demand, supply, and user preferences and feedback. Such advancements aim to enhance the overall functionality and usability of the device while concurrently reducing the need for human intervention and minimizing errors. Expanding the research scope to include various types of buildings and sectors, such as residential, commercial, industrial, and agricultural, would be instrumental. This broader perspective seeks to increase the applicability and impact of the device, catering to the diverse needs and specific characteristics of users in different contexts. A detailed and realistic cost-benefit analysis is imperative to understand the device's feasibility and attractiveness comprehensively. This analysis should consider various factors and parameters, including the initial investment, operational and maintenance costs, energy prices, carbon emissions, and social and environmental benefits. Such a comprehensive examination aims to provide a convincing justification for the viability and appeal of the device.

5 Conclusion

The developed load-shedding system, equipped with a programmable interface and time management capabilities, has demonstrated noteworthy achievements. Its functionalities include the strategic deactivation of loads during low usage periods as specified by the device, user input customization for work hours, and a consequential reduction in overall energy consumption within the building. The potential expansion of this concept envisages a centralized monitoring system for distribution points, wherein relays and circuit breakers manage the supply to designated geographical regions. This system lets users control the distribution point in response to load demands and requirements. Upon relay tripping, operators receive crucial electrical parameters, including active power, reactive power, current, voltage, frequency, and other relevant data displayed on the LCD. Utilizing a 4 X 4 keypad to interact with the microcontroller offers a practical and efficient solution for obtaining input data in a user-friendly manner. The system's ability to control load-shedding intervals based on management commands contributes to its efficiency in varying load demand and considerations in a creative office building. The prospect of implementing this system in a medium-sized creative office building, particularly at the main distribution point, underscores its potential as a sophisticated solution for optimizing energy management. This innovative approach addresses current energy challenges and opens avenues for broader applications in diverse settings, establishing its significance in advanced power systems.

JDFEWS 4 (2): 141 - 158, 2023
ISSN 2709-4529

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