Design of an SMS-Based Relay Control System for Household Energy Regulation in Rural Solar Mini-Grids

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Abstract: *Energy management remains a critical challenge in rural solar mini-grids with uncontrolled household demands leading to overloading, inefficiency and frequent blackouts. In tackling this challenge, this paper presents the design of an SMS-based relay control system to control householders' energy in rural solar mini-grids. The system architecture includes an Arduino microcontroller, a 10A relay module, and a SIM900A GSM communication unit to control loads at a distance by sending only a Short Message Service (SMS). This design uses a technology, such as GSM, that is much more likely to be available in rural areas than the internet connectivity that other IoT solutions need, which makes it more realistic in that kind of setting. Although the system was not physically constructed, the design illustrates how operators can remotely connect or disconnect household loads to prevent excessive demand, enhance grid stability, and ensure fairer distribution of energy. The proposed approach also focuses on low cost, scalability, and ease of deployment in offering a practical solution toward enhancing the reliability and sustainability of rural electrification projects. The paper contributes to the promotion of energy access by demonstrating that GSM-based control systems have the potential to effectively enhance mini-grid systems that utilise renewable energy in resource-restricted environments.*

Keywords: Control system, Solar energy, Internet of Things, Power grid, Telecommunication

1.   Introduction

Availability of affordable and dependable electricity has been a persistent challenge of most developing nations, especially rural areas where centralized grid extension may not be economically feasible. The International Energy Agency (IEA) finds that more than 500 million citizens in Sub-Saharan Africa are still without electricity, and most of them reside in rural regions where there is low population density and incomes [1]. In response, a number of decentralized solar mini-grids have also come up as a potential solution that can help the local communities in harnessing renewable sources of energy to address their household and productive requirements. The sustainability of these systems is, however, not only determined by the sufficiency of the capacity to generate it, but also by the efficiency of the energy control and management measures adopted by the operators.

Among the most pressing problems of solar mini-grids in rural areas is the absence of congruence between the changing household demand and the small capacity of the installed solar systems. The random use of loads by households usually leads to overloading of the system, voltage variations and disparities in the distribution of power that is available. The operators are hence forced to adopt demand side management methods, which can offset the loads and safeguard vital equipment. The current strategies, including prepaid meter systems and web-based monitoring systems, have gone a long way in enhancing accountability and efficiency. However, such solutions have limitations in the form of expensive installation, complexity in maintenance, and poor internet connectivity in rural areas.

Mobile communication technologies, especially the Global System of Mobile Communications (GSM) network, have, on the contrary, been shown to be more penetrating in rural areas. The Short Message Service (SMS) is specifically the low-cost, convenient, easy-to-use channel of remote operation by the operators to the household devices. Relay systems with SMS facilities enable the operators to remotely operate the connection and disconnection of the household loads to reduce the state of overload and enhance fair distribution of power [2]. In comparison to internet-based solutions, SMS commands may be effectively delivered even in regions with low connectivity and, thus, apply to rural energy settings [3].

However, even though SMS-based systems offer a great benefit in remote control, a simple, local and reliable control mechanism is also needed by the operators in rural society to control loads at the place of origin, particularly in the case of an emergency or when the GSM communication is not available at the moment. Traditionally, in manual control systems, operators have to physically apply electrical connections, which puts them at risk of electrocution. In order to overcome this drawback, they can propose safer options like the SMS-based relay control system that do not involve manipulation of the wires directly but still can be used to locally perform an intervention [4].

This paper describes the design of an SMS-based relaycontrol system incorporating the control of loads throughSMS to improve the control of household energy in rural mini-grids powered through solar. The system proposed involves the usage of a GSM module, a microcontroller, and a relay unit to maintain a reliable operation. The setup not only reduces the dangers of the manual load control,but it is also a cost-effective, scalable, and feasible solution to one of the most frequent problems with rural mini-grid energy management. This strategy is expected to be able to enhance efficiency within the system, increase the lifespan of equipment, and facilitate a fair distribution of energy across the underserved communities.

2. Literature Review

Many researchers in the past carried out work on the development of Hybrid (Manual & SMS-Based) Relay Control Systems for Household Energy Regulation in Rural Solar Mini-Grids. Their contributions motivated further research in this area. This section reviews several related studies.

Khelifa and Jelassi [5] developed a GSM-based smart energy meter for residential and small-scale consumers. It used an Arduino microcontroller, GSM, current sensors, and a relay for automatic load disconnection. The system updated consumers on real-time energy use via SMS, encouraged efficient consumption, and allowed remote load disconnection when limits were exceeded. It was affordable, scalable, and suitable for developing nations with poor internet connectivity.

Ashokkumar et al. [6] proposed an intelligent home system with relay circuits targeted at rural settings. It used a Raspberry Pi with relays and sensors for appliance scheduling and monitoring through a web-based interface. It supported security and automation functions and reduced energy waste by scheduling loads. Its strengths were simplicity and low cost, but it relied heavily on internet connectivity and lacked GSM/SMS backup.

Ofoegbu and Udoh [7] introduced an intelligent load control and power switching system using an energy meter with relay circuits. A microcontroller and relays enabled automatic load disconnection when consumption exceeded thresholds. The system was simple and affordable but depended on fixed limits and lacked remote (SMS/GSM) control.

Adika and Wang [8] suggested an autonomous appliance scheduling system for demand-side management. It automatically shifted flexible loads to off-peak periods, considering user comfort and deadlines. The method reduced hardware complexity by using algorithms instead of switching devices. However, it required reliable communication between smart meters and the grid and was less effective in areas with non-smart appliances.

Edward [9] designed an energy meter reader with load control and secure switching using a password-based relay and GSM/SMS. A microcontroller enabled remote queries, consumption monitoring, and load control via SMS with password protection. The system improved security and reduced wastage but relied solely on GSM, with possible delays, and lacked strong local override.

Rudrapal et al. [10] proposed an SMS-based load shedding control system. Utilities could send SMS commands to select substations, feeders, and duration of load shedding. It reduced manual workload and responded better to demand changes, but depended on SMS reliability and lacked field deployment data and local fail-safes.

Dragomir and Dragomir [11] examined hybrid renewable energy systems combining solar, wind, and backup sources. They highlighted improved load sharing, hybrid sizing, and efficiency. However, they gave little attention to SMS/manual load control.

Das et al. [12] developed a GSM-SMS home automation system using a microcontroller, GSM module, relays, and SMS commands. It provided device status feedback, was low-cost, and suitable for areas without internet. Weaknesses included SMS delays and no manual local control.

Saleh et al. [13] implemented a GSM-based smart home energy management system. A microcontroller with relays and sensors communicated with users via SMS. It offered remote control and status feedback, though response times were relatively long (~19 seconds) and required GSM and PC-based logic.

Wahab et al. [14] suggested a GSM-based electrical control system using a PIC microcontroller. SMS commands controlled home appliances via relays. It was simple and cost-effective but lacked feedback and local override.

Tamakloe and Kommey [15] implemented a GSM-based home appliance control system in Ghana. A microcontroller, relays, LCD, and GSM module enabled SMS-based load switching with feedback on LCD. It was simple and suitable for developing nations but limited in scope, tested only on few appliances, and lacked advanced demand-side management.

Bihari et al. [16] reviewed hybrid renewable microgrid control strategies, including AC, DC, and hybrid approaches. They noted limited focus on simple GSM/SMS or relay-based control in rural systems, motivating hybrid manual + SMS relay solutions.

Afolabi and Farzaneh [17] optimized an off-grid hybrid renewable system in Nigeria using fuzzy logic and particle swarm optimization. It reduced cost of electricity and balanced loads effectively, though it lacked hardware implementation or local/SMS control.

Gbadega et al. [18] designed a GSM-based remote controller with surge protection. It enabled SMS-based real-time load control, device status feedback, and protection. The system was safe and low-cost but dependent on GSM reliability and lacked local override.

Akorede et al. [19] created a dual-control system for outdoor security lights using SMS and WiFi. It used a microcontroller, GSM modem, WiFi, and relays. WiFi enabled cost-free local control within 100 m, while SMS supported remote operation. It improved flexibility but was limited by WiFi range, SMS delays, and scalability issues.

ElKamchouchi and ElShafee [20] developed an SMS-based home automation system with authentication via SMS (username/password). It was versatile and low-cost but lacked feedback and manual override, and SMS delays were possible.

Kaliappan [21] built a GSM-based energy meter monitoring and load control system using Arduino. It provided live SMS updates and remote control at low cost but depended entirely on GSM and lacked local override.

Prince [22] designed a microcontroller-based SMS control system. It allowed remote load switching via GSM but lacked local manual control.

Vignesh et al. [23] introduced a GSM-based load control system for home appliances. A microcontroller with relays switched loads upon SMS commands, with basic status indicators. It was simple but lacked manual override and testing on larger appliances.
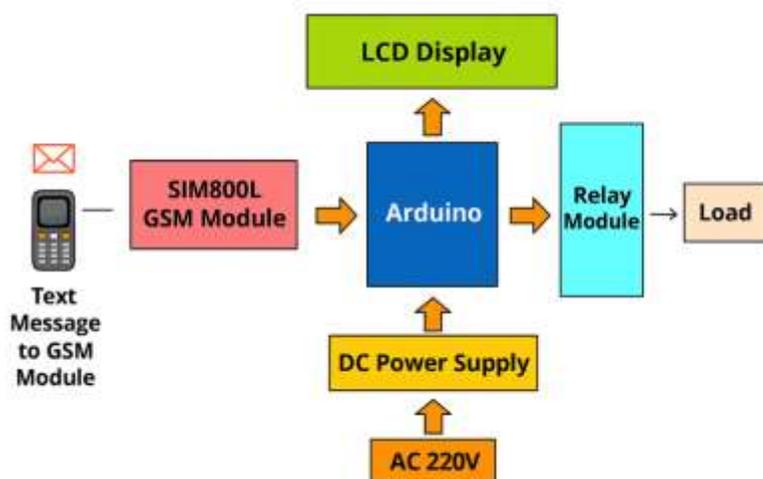
3. Materials and Methods

Fig. 1 The block diagram

The system works through communication via GSM and through the microcontroller with relay switching. When a user sends a text message using a mobile phone, it is received by the GSM module. This message is relayed to the microcontroller in the GSM module, and the Arduino microcontroller decodes this command and decides what to do. Provided the command is correct, the Arduino will activate the relay module to either switch the load attached ON or OFF based on the command sent to it. Meanwhile, the Arduino controls the LCD to give local feedback about the system status, e.g. the command received or the state of the load. The power supply unit will supply all the components with DC power that stably originates in the AC mains. This ensures consistency in the functioning of the GSM module, Arduino, display and relay. In short, the operating cycle of the system is as follows: Getting an order command via SMS,the command is processed in the Arduino,signalling the relay to switch the load,and Local monitoring of the system on the LCD. It is a simple but efficient chain that allows the remote monitoring and control of the electrical loads via GSM communication.
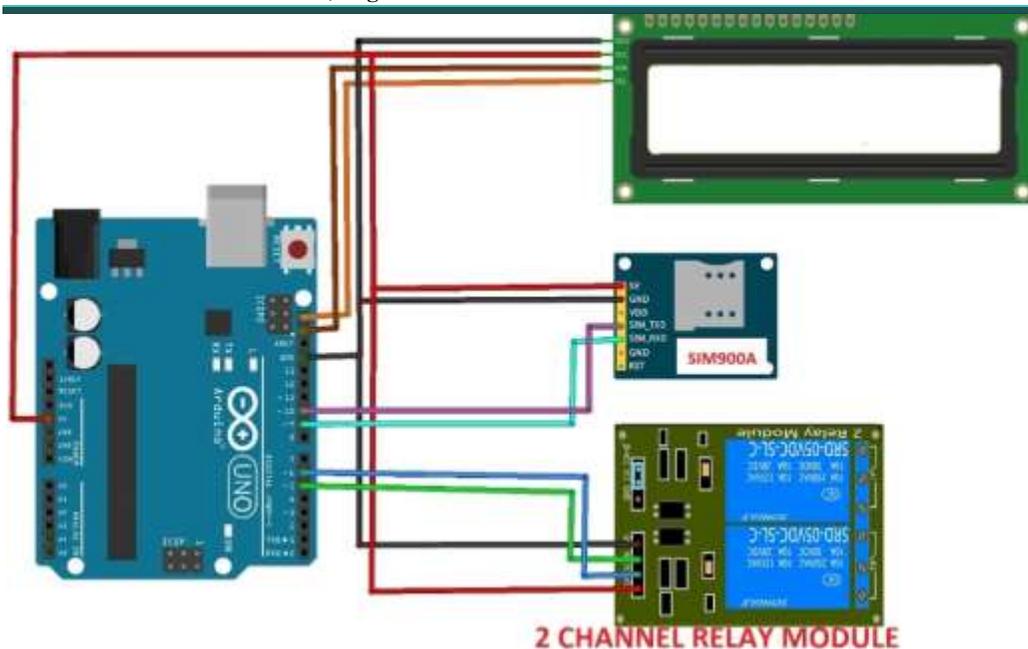
Fig. 2 The circuit diagram

The hardware components were an Arduino Uno microcontroller board, a GSM module (SIM900A), a 16x2 liquid crystal display (LCD) with an I2C interface, and a 2-channel relay module. Figure 2above shows the wiring system and interconnection between the modules.The following details are outlined about each component and role in the system:

Arduino Uno

The Arduino Uno was used as the microcontroller. It is built on the ATmega328P microcontroller that runs at 16 MHz and has 14 digital input/output pins and six analogue inputs. In this setup, the Arduino was in charge of controlling the peripheral devices, engaging the input/output activities, and processing the logic of the program. It is connected to the GSM module to communicate with the LCD to provide feedback to the user and the relay module to provide actuation.

GSM Module (SIM900A)

To facilitate wireless communication, the use of the SIM900A GSM module was used to facilitate the connection Via the Global System of Mobile Communication (GSM) network. It was compatible with sending and receiving short message service (SMS) alerts and executing remote commands. This module connected to the Arduino through the serial transmission, where the module used the TX and RX pins.

1-6x2 LCD with I2C Interface

A liquid crystal display (LCD) with 16 x 2 alphanumeric was employed in showing the real-time status of the system. The I2C module that was connected to the LCD minimized the number of pins needed to communicate with the LCD, as the Arduino could communicate with the I2C module by only two pins: SDA (data) and SCL (clock). The LCD was driven using 5 V and it showed the user messages such as the status of the system, error messages and operational messages.

2-Channel Relay Module

A two-channel electromechanical relay module was added to control high-power loads. The relays were electrically operated and could be activated by the Arduino digital pins to make or break external component connections to the mains supply. The relays had a 5 V input logic and were optically isolated to protect the Arduino to high-voltage transients.

Power Supply and Interconnections

The power supply of all the components was fed by the 5 V controlled supply on the Arduino board. The Arduino, GSM module, LCD, and relay module were connected to the common ground to make all the four modules operate in a stable state. Connection of signals between the Arduino and peripheral devices was based on standard pin allocations of UART (to GSM), I2C (to LCD), and digital output (to control relay).

4.   Discussion

The SMS-based relay control system design has a number of significant implications to the application of the solar mini-grids in the rural setting. Despite the physical implementation of the prototype not being done, the system architecture demonstrates how such a solution could help to overcome the most important difficulties in regulating the energy consumption in a household. In the conventional GSM networks, short message service (SMS) command delivery takes between a few seconds and less than half a minute, depending on network conditions. It implies that the switching of household loads may be remotely done in a comparatively short period. Although the latency of SMS communication cannot be appropriate in real-time applications requiring milliseconds response, it is applicable at the household level when energy management is needed, but instant switching is unnecessary.The primary benefits of the design are that it is based on GSM instead of the use of internet-based communication. Mobile network coverage is much greater than internet coverage in most rural and off-grid communities. This makes the system more reliable in this kind of environment. Nevertheless, one should also admit that the transfer of SMS messages may be delayed or lost in the congested network. Thus, the system will be most applicable in localities where the GSM signals are available at least moderately. It also has a relay module integrated to guarantee galvanic isolation between the low-voltage control electronics and the high-voltage household loads. This not only keeps the microcontroller safe against voltage spikes but also promotes the safety of the users as there is no longer a need to touch electrically charged wires. The design limits the chances of electrocution and equipment destruction that are prevalent in manual load switching operations since it automates the process by means of secure commands. Remote connection and disconnection of household loads is a useful management tool to the operators of rural mini-grids. It enables them to react faster to circumstances of overloading, allocate energy more equally and avoid instability of the system that frequently causes blackouts. In addition, the proposed system is affordable, easy to implement, and can be scaled, which makes it feasible to use in resource-limited environments. Through this type of system, operators may be able to improve the efficiency, sustainability and reliability of mini-grids without having to upgrade infrastructure significantly. To conclude, the system designed proves the potential of GSM-based relay control as a safe and low-cost solution to rural electrification problems. The work in the future should be aimed at the realization of the physical prototype, system testing during the concrete load conditions and introduction of such features as local manual override and data logging to monitor the system long-term.

5.   Conclusion

This paper has presented the design of an SMS-based relay control system for household energy regulation in rural solar mini-grids. The system integrates a GSM communication module, an Arduino microcontroller, an LCD interface, and a relay switching unit to provide remote load management through simple SMS commands. Unlike internet-based solutions, which are often impractical in rural environments, GSM technology offers a more reliable and accessible communication channel.

The discussion has highlighted the expected response time of SMS-based commands, the reliability of GSM in rural networks, and the safety benefits of relay isolation. By enabling operators to remotely connect or disconnect household loads, the system provides a practical means of preventing overload, ensuring fair energy distribution, and reducing the risk of blackouts. These features can significantly enhance the efficiency, sustainability, and reliability of rural mini-grids while maintaining low implementation cost and ease of deployment.

Although the work presented is limited to system design without physical construction, it establishes a clear framework for future implementation. Further research should focus on building a prototype, testing performance under real operating conditions, and extending the design with additional features such as local manual overrides, feedback mechanisms, and data logging for long-term monitoring.

In conclusion, the proposed GSM-based relay control system offers a cost-effective, safe, and scalable solution that can support rural electrification projects and contribute to broader efforts toward sustainable energy access.

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