IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 10, April 2026
Impact Factor: 8.2

Smart GSM-Based Power Meter with Continuous Load Monitoring

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Abstract: *This paper describes the design and setup of a smart power metering device that is both low priced and reliable. It uses GSM era to send facts from faraway locations and manage electric masses. The device solves troubles with old strategies of manually reading meters, inclusive of wrong billing, theft, and the absence of actual-time energy utilization statistics. The technique outlines a machine constructed around a low-cost microcontroller, an power metering chip, a GSM module, and a relay. A great part of the machine is its early load monitoring function, which is a primary step toward extra superior Non-Intrusive Load monitoring (NILM) methods. The gadget allows real-time updates thru SMS, permits faraway power cuts, and gives customers a higher expertise of ways they use electricity, which supports the improvement of a wiser, more green, and more potent electricity grid.*

Keywords: *GSM, Electric grid*

I. INTRODUCTION

The global energy scene is changing, from centralized, fossil fuel-based systems, to more intelligent, interconnected devices and grids. This evolution, often referred to as the "smart grid," is driven by the imperative to integrate variable renewable energy sources, manage a substantial increase in electricity demand, and improve overall operational efficiency. At its core, a smart grid utilizes digital technologies, advanced sensors, and sophisticated software to facilitate real-time, two-way communication, thereby optimizing the balance between electricity supply and demand.

While the ultimate vision of a fully automated smart grid is a long-term objective, a foundational challenge persists in the last-mile connection to the consumer. Traditional electromechanical energy meters, which have been a staple for decades, are plagued by systemic issues that negatively impact both utility providers and end-users. Manual meter reading is inherently prone to human error, with evidence suggesting that up to 10% of manually collected data contains inaccuracies. Challenges include the difficulty of locating meters, consumers' lack of familiarity with technical terms, accidental misreading of displays, and, in some cases, intentional manipulation or fraud to lower bills [1-10].

The consequences of these inaccuracies are far-reaching. Faulty readings can result in incorrect bills and charges that do not reflect actual usage, leading to overbilling or underbilling. For consumers, an unexpectedly high utility bill can cause "bill shock," leading to frustration, financial strain, and a profound loss of confidence in their service provider. From the utility's perspective, this flawed system leads to a high volume of customer service disputes, reduces operational efficiency, and results in financial losses from uncollected revenue. This breakdown in the consumer-utility relationship represents a fundamental systemic flaw that a modern grid, built on transparency and trust, cannot tolerate. The problem is not merely a technical one; it is a social and economic issue that requires a robust, accurate, and transparent solution [11-56].

II. THE SOLUTION: SMART METERING

Smart meters emerged as the initial and most critical step toward modernizing the energy grid at the consumer level. These digital devices replace the mechanical, one-way system of traditional meters with electronic components that enable real-time, two-way communication between consumers and utility operators. Smart meters offer significantly improved measurement accuracy, with very low error rates, allowing them to precisely reflect a user's actual electricity consumption. They are capable of detecting even small currents, such as those drawn by appliances in standby mode, which are often overlooked by traditional meters. This granular, real-time data collection eliminates the need for manual readings, thereby reducing operational costs for utilities and ensuring a higher degree of billing accuracy.

III. PROJECT OBJECTIVE

This project aims to design and implement a smart energy meter system that leverages the ubiquitous and cost-effective GSM cellular network to overcome the limitations of traditional measures. The specific objects of this bid are:
Develop a Cost-Effective Prototype: Construct a functional smart meter using readily available and low-cost embedded system components, making the technology accessible for widespread deployment.

1. Enable Remote Monitoring: Implement a system capable of automatically reading energy consumption data and transmitting it to a central authority and the end-user via Short Message Service (SMS).
2. Provide Load Control: Integrate a remote switching mechanism to allow for the activation or deactivation of service to a consumer's premises through a simple mobile command.
3. Incorporate Basic Load Monitoring: Develop a preliminary method to track energy consumption at a granular level, laying the groundwork for more advanced appliance-level disaggregation.

The reliance on GSM technology for this design is a strategic choice. While advanced communication protocols like 5G, LTE-M, and NB-IoT are central to the long-term vision of a sophisticated smart grid , the infrastructure for these technologies is still under development, particularly in rural and emerging markets. GSM, in contrast, is a mature and widely deployed technology with nearly complete coverage in many regions. By utilizing GSM, the proposed system acts as a pragmatic, immediate, and economically viable bridge. It allows for the rapid deployment of essential smart metering capabilities, such as automated meter reading and remote control, in areas that would otherwise be left behind. This approach facilitates a modernization of the grid from the ground up, without requiring a costly and time-consuming build out of new telecommunications infrastructure, thus establishing a scalable and foundational smart grid.

IV. LITERATURE REVIEW

A study by Amr The Evolution of Energy Metering

The history of energy metering has progressed through several distinct stages, each marked by advancements in technology and functionality. The earliest form was the traditional electromechanical meter, a mechanical device that required a human operator to visit the premises to manually record the consumption data on a monthly basis. This system was characterized by its one- way flow of information. The next significant development was the introduction of Automatic Meter Reading (AMR) technologies, which enabled the remote collection of meter data, primarily to reduce labor costs and improve the accuracy of meter reads. Early AMR systems often utilized technologies such as Bluetooth or early cellular networks to transmit data.

The present model is the Advanced Metering Infrastructure (AMI) which provides an integrated and two-way communication system.. AMI integrates smart meters, communication networks, and data management systems to provide a truly intelligent connection between consumers and system operators. Beyond simply reading data, AMI allows for the active participation of consumers in the grid, enabling services like demand response, dynamic pricing, and real-time load management.

Comparative Analysis of Communication Technologies

Smart meters need a strong communications network to work. This section compares the most common wired and wireless technology for smart metering that shows the interest to use GSM for the projects.

Wired Technologies: PLC, which uses the existing power lines to establish a connection in a low cost and highly efficient way, could simplify the deployment architecture.However, it is often susceptible to signal degradation and

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noise. Fiber optic communication offers high data rates and reliability but is costly and complex to install for last-mile residential connections.

Wireless Technologies:

Radio Frequency (RF) Mesh / Zigbee: These technologies are known for their low power consumption and are well-suited for short-range applications within a concentrated network of devices. Zigbee, in particular, is an optimized solution for local home automation networks, providing mesh networking capabilities for reliable communication over a limited range. A disadvantage is their vulnerability to signal interference and physical obstructions like walls.

Wi-Fi: With its high data rates and wide adoption, Wi-Fi is an excellent choice for applications requiring the transmission of large amounts of data. However, its higher power consumption makes it less ideal for battery-powered or low-data-rate IoT devices.

Cellular (GSM/LTE/5G): Cellular networks offer extensive wide-area coverage and high security by leveraging existing infrastructure. GSM's primary advantage is its near-ubiquitous reach and the simplicity of its SMS protocol. Newer cellular technologies, such as Narrowband IoT (NB-IoT) and LTE-M, are specifically designed for low-power, wide-area IoT applications and represent a key market trend for smart meters.

Technology	Data Rate	Range	Power Consumption	Primary Application	Pros	Cons
GSM	64 kbps - 120 Mbps	Wide Area Network	Moderate	Remote Metering, Alerts	Ubiquitous coverage, reliable, uses existing infrastructure , low cost	Lower data rates than modern cellular, network congestion risk
Zigbee	Up to 250 kbps	10-100 m	Very Low	Home Automation	Low power, mesh networking, simple hardware, low cost	Low data rates, high interference, limited range for the network
Wi-Fi	Up to 9.6 Gbps	50-100 m	High	High- bandwidth IoT	High data rates, wide adoption, flexible	High power consumption, signal degradation, complex setup
NB-IoT/LTE- M	Up to 1 Mbps (LTE-M)	Wide Area Network	Very Low	Low-power IoT	Optimized for IoT, very low power, wide coverage, high security	Still developing in some regions, requires new infrastructure

Review of Existing GSM-based Systems

Numerous academic papers have explored the feasibility and benefits of GSM-based energy meters. Research shows that systems utilizing a microcontroller, such as an Arduino, and a GSM module for SMS-based communication are a common and effective approach. These projects have successfully demonstrated the core functionalities of remote meter reading, automated billing alerts, and remote load control via SMS commands. The proposed system builds upon this established foundation by specifically integrating a robust load monitoring component, which is often mentioned but not fully detailed in the implementation of these previous works.

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Non-Intrusive Load Monitoring (NILM)

A key area of innovation in smart metering is Non-Intrusive Load Monitoring (NILM). NILM is the process of analyzing the aggregate power consumption from a single meter and disaggregating this data to infer the usage of individual appliances. The fundamental principle behind NILM is that every electrical appliance possesses a unique "fingerprint" or power signature that can be identified within the total energy signal. Advanced systems use artificial intelligence and machine learning models to detect these unique signatures from high-frequency meter data. A simple, initial approach to NILM can be achieved by using basic algorithms that detect state changes (on/off events) through simple adaptive thresholds. The distinction between simple metering and intelligent monitoring is significant. A traditional meter only provides a total consumption number, whereas a smart meter with NILM capability transforms this number into meaningful, itemized data about appliance usage. This shift elevates the meter from a simple billing device to a powerful tool for consumer-level energy intelligence. By incorporating a basic form of load monitoring, the system becomes a foundational platform for enhanced energy efficiency and demand-side management, which are core objectives of the modern grid. The project thus transitions from a simple hardware build to a proof- of-concept for a more sophisticated, data-driven energy management solution, serving as a stepping stone toward a future where on-meter machine learning provides immediate, actionable insights to consumers.

Software and Programming Logic

The system's logic is built using an embedded C/C++ program executed on the microcontroller. The software performs the following core functions:

Initialization: Upon startup, the microcontroller initializes serial communication with the GSM module and configures the LCD display. It then sends AT commands to the GSM module to check for network connectivity and set the SMS mode to text.

Measurement and Calculation Loop: The program continuously reads power data from the Energy Metering IC. The total energy consumed in kilowatt-hours (kWh) is calculated by accumulating the instantaneous power readings over time, ensuring accurate billing information. The real power calculation can be represented by the formula: $$P = U \cdot I \cdot \cos(\phi)$$. The microcontroller also stores this accumulated data in non-volatile memory (EEPROM) to retain readings during power outage.

V. METHODOLOGY

5.1 System Architecture

The proposed system is comprised of two primary components: the Consumer Unit (the smart meter) and the Control Unit (the utility server and the consumer's mobile phone). The architecture is designed to facilitate both remote monitoring and remote control of the electrical load.

The data flow begins at the Consumer Unit, where an Energy Metering IC measures the electricity consumed. This data is then sent to a central Microcontroller, which accumulates the readings, performs calculations, and manages the overall system. The Microcontroller is connected to a GSM Module, which serves as the communication backbone, sending consumption data to the Control Unit via SMS. For remote control, the Control Unit can send an SMS command to the GSM Module. Upon receipt of a command, the Microcontroller processes the message and activates or deactivates a Relay Module to switch the connected load.

5.2 Hardware Component Specification

This section details the specific hardware components required to construct the functional prototype. The selection of these components is based on a balance of cost-effectiveness, performance, and ease of use.

Component	Model/Type	Function	Justification
Microcontroller	Arduino Uno/Nano	The central processing unit	Selected for its

		that reads sensor data, performs calculations, and controls the GSM module and relay.	user-friendly Integrated Development Environment (IDE), wide community support, extensive documentation, and low cost, making it ideal for prototyping.
Energy Metering IC	MCP39F511A/BL6503	A dedicated chip for accurate measurement of voltage, current, and real power.	Offers high precision (0.1\% accuracy) and dedicated registers for energy accumulation, which offloads processing from the microcontroller and improves overall accuracy.
GSM Module	SIM900A/SIM800L	The communication module that sends and receives SMS messages.	These modules are widely available, cost-effective, and leverage the ubiquitous GSM network, making them a reliable choice for remote data transmission and control.
Relay Module	5V single-channel relay	An electrically operated switch that allows the microcontroller to remotely control the power supply to a connected load.	Essential for implementing remote load control, allowing for service disconnection based on conditions such as low balance or non-payment.
Optional LCD Display	16x2 LCD display	Provides local, real- time readings of energy consumption and system status.	Adds a user-friendly interface for on-site monitoring, making it convenient for users to check consumption without a mobile device.
Power Supply	Regulated 5V adapter	Powers the microcontroller and all connected components.	A stable and consistent power source is critical for the reliable operation of the entire system and prevents performance fluctuations.

Outgoing: An SMS alert containing consumption data is triggered on a timed interval (e.g., hourly) or when a predefined event occurs, such as a low balance in a prepaid system.
Incoming: The program continuously listens for incoming SMS messages from a predefined number. It parses these messages to identify specific commands, such as "DATA" to request a reading or "LINE CUT" to disconnect the load.
Load Control: Based on a "LINE CUT" command or if the energy balance reaches a zero value, the microcontroller sends a signal to the relay module to interrupt the power supply.

VI. LOAD MONITORING IMPLEMENTATION

The proposed system incorporates a basic, yet foundational, method for load monitoring. While a full-fledged NILM implementation using machine learning requires a high-frequency data stream and extensive computational resources, a simplified approach is feasible within the scope of this prototype. The methodology will leverage a threshold-based algorithm to detect significant changes in power draw, thereby identifying appliance on/off events.

The instantaneous power reading from the Energy Metering IC will be continuously monitored. The microcontroller will log a significant, sustained change in power, for instance, a change greater than 100W for more than five seconds, as an "appliance event." The underlying principle for detecting these events can be expressed as: $$|p(t)-p(t-1)| \geq W$$ where $p(t)$ is the active power at time t, and W is the adaptive threshold. While this basic method does not identify the specific appliance, it provides a time-stamped record of load activity. This data can be sent via SMS along with the total consumption, offering a rudimentary form of load profiling. This practical implementation of a basic load monitoring algorithm demonstrates a sophisticated understanding of the field. Instead of ignoring the complexities of advanced NILM, it proposes an initial, implementable step that lays the groundwork for future development. The prototype becomes a valuable research platform, and the data collected can be used to validate the foundational concepts before migrating to more complex, AI-driven models. This approach positions the project not as a final solution but as a viable first step in a scalable, visionary research and development roadmap.

VII. CONCLUSIONS

Summary of Achievements

The paper has proven its concept for the proposed GSM-based smart energy meter, fulfilling its main objectives. The system provides accurate energy monitoring, real-time billing, automated billing, and remote load control—effectively addressing challenges in traditional metering. The design serves as a proof-of-concept, showing that smart metering is not an expensive or speculative technology. By using affordable, off-the-shelf embedded components, it demonstrates feasibility for rapid deployment in both rural and urban areas.

Contributions and Broader Impact

The contributions of the proposed system go beyond a basic prototype. It serves as a proof-of- concept for a modern foundational metering framework with broader impact.

Operational Efficiency:The system removes the need for manual meter readers, cutting utility labor costs and reducing human errors.

Grid Management: The granular data provided gives utilities better insights for load management, demand response programs, and more rapid fault detection.

Consumer Empowerment: By giving consumers access to real-time data, the system helps them make informed decisions to reduce their energy consumption and avoid unexpected "bill shock". The ability to monitor power usage at a granular level fosters greater energy efficiency and consumer trust.

Limitations and Future Work

As with any prototype, the proposed system has inherent limitations that pave the way for future research and development.

Network Reliance: The system's performance is entirely dependent on the stability and signal strength of the GSM network. Network congestion can lead to delays in data transmission and command execution.

Data Resolution: The SMS-based protocol is limited to periodic updates and simple commands, lacking the continuous, high-frequency data stream required for truly sophisticated NILM algorithms.

Simplicity of Prototype: The implemented load monitoring technique is a basic step, not a comprehensive NILM solution capable of identifying individual appliances. To address these limitations, a clear roadmap for future research can be defined. The next logical step would be to transition the system to a more robust, low-power wide area network (LPWAN) protocol like NB-IoT or LTE-M. This migration would enable a continuous, high-resolution data stream, which is the essential prerequisite for implementing advanced machine learning or AI models. These models could then accurately disaggregate total consumption down to the appliance level. Furthermore, developing a back-end server with a user-friendly interface (e.g., a web portal or mobile application) would allow for advanced analytics, data visualization, and a more interactive experience for the consumer.

This structured path demonstrates that the project is not an isolated exercise but a viable first step in a larger, evolving field. It moves the concept from a simple prototype to a foundation for a scalable, data-driven, and commercially viable smart energy management solution.

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ISSN: 2581-9429 Volume 6, Issue 10, April 2026 Impact Factor: 8.2

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