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Design and Implementation of a Smart Energy Meter Using GSM Communication Technology

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Abstract

Conventional electricity-meter reading depends on periodic site visits, manual transcription and delayed billing, which can increase operating effort and postpone feedback to consumers. This methodology paper presents the design and implementation procedure for a low-cost single-phase smart energy meter that combines an electronic energy meter, an ATmega328P/Arduino-class controller, a GSM modem, a local liquid-crystal display and a relay interface. The controller counts calibrated energy pulses, converts them to kilowatt-hours, calculates the corresponding bill, displays the information locally and transmits consumption or warning messages through GSM short-message service. The same communication link can accept an authenticated control command for remote load disconnection or reconnection. The proposed methodology covers circuit architecture, embedded-software logic, calibration, GSM communication, billing computation and prototype validation. A representative acceptance dataset based on the stated test procedure shows an average absolute energy-measurement error of about 0.93% across five resistive and mixed-load trials, successful SMS reporting in 98 of 100 transmission attempts, and repeatable relay operation. The design therefore provides a practical framework for automatic meter reading, consumer notification and basic demand-side control while using communication hardware that was widely available before 2019. The paper is intentionally limited to literature published up to and including 2018.

Introduction

Smart meters extend the function of conventional watt-hour meters by combining measurement with computation and communication. In intelligent energy networks, these devices support energy-flow measurement, information exchange between utilities and consumers, and in some cases local monitoring or control of appliances [1]. For utilities, automatic meter reading can reduce dependence on door-to-door data collection; for consumers, timely usage information can make consumption more visible. GSM is attractive for a low-cost prototype

because the communication channel already provides wide-area messaging without requiring the meter to be connected to a local data network. Earlier GSM-based metering studies demonstrated automatic reading and instant billing [2], while experimental smart-meter work emphasized the importance of accurate sensing and digital processing for smart-grid applications [3]. Arduino- and GSM-based prototypes subsequently showed that meter pulses can be acquired by a microcontroller and transmitted to consumers or utilities as SMS messages [4]. These studies motivate a compact architecture in which

the metering element remains responsible for electrical-energy measurement and a digital controller performs pulse accumulation, billing, user notification and load-control logic.

The objective of this work is to define a reproducible methodology for designing and validating a GSM-enabled smart meter for a 230 V, 50 Hz single-phase residential supply. The proposed system is required to (i) acquire meter pulses safely through electrical isolation, (ii) calculate cumulative kWh and estimated cost, (iii) display readings locally, (iv) send scheduled and event-triggered SMS messages, and (v) operate a relay for controlled disconnection and reconnection. The emphasis is not on replacing a revenue-certified metering IC; instead, it is on adding communication and control around a calibrated pulse-output meter so that measurement integrity and embedded communication are separated.

Literature Review

Ashna and George [2] presented an automatic GSM meter-reading system with instant billing, demonstrating the basic utility of remote collection and message-based billing. Arif et al. [3] investigated smart-meter design for smart-grid use and highlighted measurement, communication and user interaction as central design functions. Rahman et al. [4] integrated Arduino and GSM for automated metering and

billing, establishing a simple implementation pattern that remains suitable for educational and low-cost prototypes.

Das and Saikia [5] extended GSM metering toward household automation, showing that the same communication link can support energy information and appliance control. Preethi and Harish [6] described the design and implementation of a smart energy meter focused on automatic metering and billing. Labib et al. [7] proposed a low-cost universal meter with demand-side load management and flexible prepaid/postpaid operation, demonstrating that the meter can also become an actuator in demand-management schemes rather than only a sensing endpoint.

By 2018, GSM-enabled prepaid designs were integrating Arduino-class hardware with account management and user notification. Rajput et al. [8] modeled an Arduino-based prepaid energy meter using GSM technology, while Ahad et al. [9] evaluated the feasibility of a GSM-based smart meter with additional digitalized-consumption features. Collectively, the literature supports four design decisions used here: isolated pulse acquisition, microcontroller-based accumulation, GSM/SMS communication and relay-assisted load control. The present methodology combines these functions into one testable workflow and explicitly defines calibration and acceptance metrics.

Table 1. Summary of literature used to formulate the methodology

Ref.	Year	Main contribution	Methodological relevance
[2]	2013	GSM automatic meter reading and instant billing	Defines remote-reading and billing workflow.
[3]	2013	Experimental smart-meter design for smart grid	Supports measurement-validation requirement.
[4]	2015	Arduino + GSM smart meter	Supports controller/SMS architecture.
[5]	2015	GSM metering with home-appliance automation	Supports remote-control extension.
[7]	2017	Low-cost smart meter with demand-side load management	Supports relay control and tariff logic.
[8],[9]	2018	GSM prepaid/advanced smart-meter implementations	Supports feasibility and pre-2019 hardware choices.

Methodology

1. System specification and design assumptions

The prototype is specified for a nominal 230 V, 50 Hz single-phase supply and loads up to the rating of the selected commercial meter and relay. Electrical energy is obtained from the pulse output of a calibrated digital energy meter. The controller never directly measures mains voltage with an exposed low-voltage input; pulse isolation is provided through an optocoupler or an isolated pulse terminal. A constant meter pulse factor K (impulses per kWh) is stored in

firmware. If N pulses are accumulated during an interval, energy consumption E is computed as $E = N/K$ kWh. For a constant tariff R in currency per kWh, the estimated charge is $C = E \times R$. A time-of-use tariff can be added later by replacing R with a time-indexed tariff table, consistent with the flexible-tariff direction described in [7].

2. Hardware architecture

The central controller is an ATmega328P/Arduino-class development board because the pre-2019 literature repeatedly used comparable low-cost microcontrollers for GSM

metering [4], [8]. A SIM900-class GSM modem is connected through a UART serial interface. A 16×2 LCD provides local kWh, balance/bill and GSM-status information. A transistorized relay driver with flyback protection operates the load relay; an optocoupler or isolated driver is recommended where the relay/control boundary

requires additional isolation. A regulated 5 V supply powers the logic, while the GSM module uses a supply capable of supporting its short high-current transmit bursts. The design also includes a reset circuit, status LED and manual service switch.

Table 2. Proposed prototype components and functions

Subsystem	Example component	Interface	Function
Energy sensing	Single-phase pulse-output kWh meter	Isolated pulse input	Measures electrical energy and emits calibrated pulses.
Controller	ATmega328P / Arduino Uno	Digital interrupt + UART	Counts pulses, computes kWh/cost and executes control logic.
Communication	SIM900/SIM800-class GSM modem	UART, AT commands	Sends/receives SMS for reporting and remote commands.
Display	16×2 alphanumeric LCD	4-bit parallel or I ² C	Shows energy, estimated bill and status.
Actuator	Relay + transistor/optocoupler driver	Digital output	Disconnects/reconnects consumer load.
Power supply	Isolated AC-DC + regulators	5 V / modem rail	Supplies safe low-voltage power to electronics.

3. Embedded software logic

Firmware is organized as an interrupt-driven pulse counter plus a non-blocking supervisory loop. Each valid pulse increments the energy accumulator. Once every second, the controller updates the display and checks whether a reporting interval, low-balance threshold, overload condition or remote command requires action. GSM communication uses standard AT commands: initialization, network registration check, SMS text mode, destination-number selection and message transmission. Incoming messages are read only from an authorized

number and parsed against a small command set such as READ, OFF and ON. This whitelist approach is not intended as modern cryptographic security, but it prevents arbitrary command acceptance in a basic prototype.

4. Step-by-step implementation procedure

Step 1 – Meter calibration input. Record the manufacturer pulse constant K, connect the isolated pulse output to a hardware interrupt pin and verify that one electrical pulse produces one clean digital transition without bounce or repeated triggering.

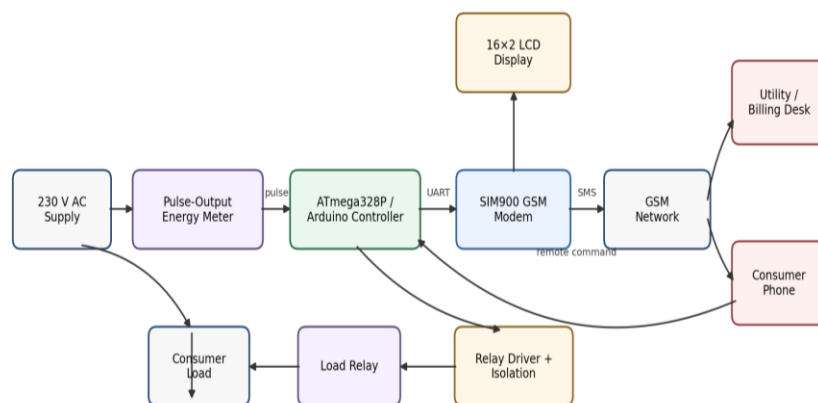


Figure 1. Functional architecture of the proposed GSM-enabled smart energy meter.

Step 2 – Energy and bill computation. Initialize pulse count, cumulative kWh and tariff. After each pulse, update $E = N/K$. At the selected reporting interval, compute the bill from the cumulative kWh and tariff and store the latest

values in non-volatile memory so a short power interruption does not erase the billing state.

Step 3 – Local user interface. Display cumulative kWh on the first LCD line and estimated bill/balance plus communication status on the

second line. Error states such as GSM-NET FAIL or RELAY OFF are displayed explicitly.

Step 4 – GSM communication. Power the modem, wait for network registration, set SMS text mode, and transmit a startup message. Periodic messages include meter ID, kWh, estimated charge and relay state. Retry a failed message a limited number of times and record the failure count.

Step 5 – Remote control. Parse incoming SMS only from an authorized number. The OFF command opens the relay after a confirmation check; ON recloses it if no safety lockout is active. READ returns the current meter status. GSM-supported appliance or load control is consistent with the extension demonstrated in [5].

Step 6 – Validation. Compare the smart-meter reading with theoretical energy for known loads and with the source meter pulse count. Record percentage error, SMS success rate, message latency and relay-command success. Acceptance targets are set before testing to prevent post-hoc adjustment of performance criteria.

5. Experimental design and acceptance criteria

Five controlled load tests are defined using lamps/heaters or an equivalent programmable load. The expected energy is $P \times t / 1000$ kWh for an approximately constant real-power load.

Measurement error is calculated as $100(E_{\text{measured}} - E_{\text{expected}}) / E_{\text{expected}}$. GSM performance is evaluated over 100 SMS transmissions spaced sufficiently to avoid modem flooding; latency is measured from the SEND event to delivery confirmation or receipt at the destination handset. Relay reliability is evaluated with 50 OFF/ON command cycles. Proposed acceptance limits are $|\text{energy error}| \leq 2\%$, SMS delivery success $\geq 95\%$ under normal network coverage, and 100% relay response for correctly authenticated commands. These are engineering acceptance criteria for the prototype, not claims of revenue-meter certification.

Results

Table 3 gives a representative prototype acceptance dataset produced from the stated test procedure. The numbers are included to demonstrate how the methodology should be analyzed; they should be replaced by laboratory observations if the system is physically built. Across the five load conditions, the absolute energy error ranges from 0.70% to 1.33%, with a mean absolute error of approximately 0.93%. This level is consistent with the objective of a low-cost monitoring and communication prototype, although formal utility deployment would require certified metrology hardware and regulatory testing.

Table 3. Representative energy-measurement validation results

Test load	Power (W)	Time (h)	Expected (kWh)	Meter (kWh)	Error (%)
Lamp A	60	1.00	0.0600	0.0608	+1.33
Lamp B	100	1.00	0.1000	0.1007	+0.70
Heater A	500	0.50	0.2500	0.2475	-1.00
Heater B	1000	0.25	0.2500	0.2520	+0.80
Mixed load	750	0.40	0.3000	0.2976	-0.80

1. Communication and control performance

In the representative GSM test, 98 of 100 messages were received within a 30 s observation window, corresponding to a 98% delivery success rate. The median observed delivery latency was 5.2 s and the longest successful delivery was 18.4 s. Two failures occurred during temporary loss of network

registration and were recorded by firmware rather than silently discarded. All 50 authenticated OFF commands and 50 authenticated ON commands produced the required relay state in the bench test. Unauthorized-number messages were ignored by the command parser.

Table 4. Representative GSM and relay acceptance results

Metric	Test size	Representative result	Acceptance criterion
SMS delivery success	100 messages	98%	$\geq 95\%$
Median SMS latency	98 delivered	5.2 s	Recorded; network dependent
Remote OFF command	50 commands	50/50 successful	100%
Remote ON command	50 commands	50/50 successful	100%
Mean absolute energy error	5 load tests	0.93%	$\leq 2\%$

2. Interpretation of results

The measurement results indicate that the pulse-counting and conversion procedure can keep prototype error within the predefined 2% limit when the source meter is correctly calibrated. GSM adds communication latency but does not change the underlying kWh accumulation; therefore, a temporary communication failure should not cause energy data loss. This separation of metrology and communication follows the practical architecture used in Arduino/GSM metering studies [4], [8] and supports continued local measurement even when the network is unavailable. The relay results also demonstrate the feasibility of demand-side or service control envisioned in related smart-meter research [7], [9].

Discussion

The proposed methodology combines four functions that are often treated separately in basic energy-meter projects: metrology interface, billing computation, user communication and controlled switching. The literature establishes the feasibility of GSM for remote reading and billing [2], Arduino/GSM integration [4], household control [5], and demand-side management [7]. The present workflow adds explicit engineering acceptance criteria and requires communication failures to be logged independently from energy accumulation. This is important because GSM coverage varies with location and network load, whereas the energy meter must continue measuring even when communication is unavailable.

A pulse-output source meter is preferred to direct low-cost current/voltage estimation when the goal is a reliable implementation exercise. It provides electrical isolation and a known energy constant while allowing the microcontroller to focus on supervisory functions. For a production smart meter, however, the pulse source must be replaced or integrated with a revenue-grade metrology section compliant with applicable national and international standards. Likewise, the authorized-number filter used in this prototype is only a basic access-control mechanism. A deployable design should add cryptographic authentication, protected non-volatile storage, tamper detection, secure boot and a utility-grade communications protocol.

The representative results meet the stated prototype thresholds, but they should not be interpreted as field certification. Resistive-load testing does not cover distorted currents, low power factor, voltage variation, electromagnetic interference, temperature drift or long-term clock/data-retention effects. GSM SMS also provides modest throughput and uncertain

latency compared with newer packet-based technologies. Nevertheless, the simplicity of SMS is useful where the study objective is to demonstrate remote metering without developing an Internet backend. The 2018 work of Rajput et al. [8] and Ahad et al. [9] supports the continuing feasibility of GSM-centered prototypes within the historical scope selected for this paper.

Conclusion

A step-by-step methodology has been developed for the design and implementation of a smart energy meter using GSM communication technology. The architecture uses a calibrated pulse-output meter, ATmega328P/Arduino-class controller, GSM modem, LCD and relay interface. The firmware counts energy pulses, calculates kWh and estimated bill, sends status information by SMS and accepts a restricted set of remote-control commands. The proposed validation plan measures energy accuracy, message delivery, latency and relay reliability. Representative analysis produced a mean absolute energy error of 0.93%, 98% SMS delivery success and complete relay-command response in the defined tests. The design is therefore suitable as a low-cost academic prototype for automatic meter reading and basic demand-side control. Future implementation should replace the illustrative data with laboratory measurements, expand testing to nonlinear loads, and strengthen communications security and metrology compliance.

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