



Design and Performance Evaluation of Smart Energy Metering Systems Using Microcontroller-Based Technology

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Peer Review Information

Submission: 23 Jan 2018

Revision: 11 Feb 2018

Acceptance: 21 March 2018

Keywords

*Smart Energy Meter,
Microcontroller, Automatic
Meter Reading, GSM/IoT,
Energy Monitoring.*

Abstract

Smart energy metering combines electrical measurement, embedded processing, communication, and load-control functions to improve the accuracy and availability of consumption information. This methodology paper presents the design and performance-evaluation framework for a low-cost microcontroller-based smart energy meter suitable for residential and small commercial loads. The proposed architecture uses isolated voltage and current sensing, analog-to-digital conversion, microcontroller-based calculation of RMS voltage, RMS current, active power, and accumulated energy, a local display, a communication interface, and relay-based load control. Performance is evaluated using calibrated reference inputs at multiple load levels and power factors. The principal indicators are energy-measurement error, response time, communication success rate, control latency, and functional reliability. A simulation-based benchmark demonstrates how the protocol can quantify expected accuracy and communication performance before hardware field deployment. The approach emphasizes modularity, low computational overhead, and compatibility with automated metering infrastructure. The methodology provides a reproducible basis for comparing microcontroller-based smart-meter prototypes while identifying calibration, communication reliability, and security as the main issues requiring validation in a final laboratory or field implementation.

Introduction

Electricity metering has developed from electromechanical accumulation meters toward electronic meters capable of remote reading, two-way communication, event recording, and demand-side control. Conventional manual meter reading is labor-intensive, delays billing information, and can introduce transcription errors. Early automatic meter reading (AMR) studies therefore combined digital energy measurement with GSM/GPRS communication so that utilities could obtain consumption information without visiting the consumer premises [1], [2]. The same embedded architecture also created opportunities for

tamper alarms, prepaid functions, remote disconnection, and consumer feedback.

Microcontrollers are especially suitable for low-cost smart meters because a single programmable device can acquire voltage and current samples, calculate electrical quantities, store accumulated energy, update a display, handle communication, and operate protection or disconnection relays. A prepaid metering model was proposed as an approach to reduce non-technical losses and improve revenue collection [3], while Arduino-GSM systems demonstrated that embedded controllers can automate billing and transmit consumption information through existing cellular networks

[4]. These developments shifted the meter from a passive measurement instrument to an active endpoint of the smart grid.

At the system level, smart metering is a core component of advanced metering infrastructure (AMI), in which meters exchange information with data concentrators and utility systems. Reviews of smart-metering technology identify metering accuracy, communication interoperability, data handling, and security as essential design concerns [5]. AMI research also emphasizes that communication technology and meter hardware/software must be designed together because inadequate network reliability can reduce the usefulness of otherwise accurate meters [6]. Smart-meter data further supports load analysis, demand response, household energy management, and forecasting [7].

The objective of this paper is therefore to define a reproducible methodology for designing and evaluating a microcontroller-based smart energy meter using technologies available up to 2018. The study focuses on five questions: whether the sensing and computation chain can achieve acceptable energy-measurement accuracy; whether the selected microcontroller can execute measurement, display, communication, and control tasks in real time; whether remote data transfer is sufficiently reliable; whether relay commands are executed with low latency; and whether the complete design remains modular and economically implementable. The contribution is a step-by-step experimental framework that can be implemented with an ATmega328P-class, ARM Cortex-M, or comparable microcontroller and then extended to GSM, Wi-Fi, or other AMI communication technologies.

Literature Review

Low-cost remote metering research initially concentrated on replacing manual reading. Al-Omary et al. [1] developed a secure GPRS-based AMR architecture with a digital meter, transmission facility, and billing server. Jain et al. [2] similarly used GSM communication for remote energy information, load status, power cut reporting, and tamper-related functions. These studies established the practical value of cellular communication but placed less emphasis

on detailed computational performance inside the meter.

Research then expanded toward payment control and utility loss reduction. Mohammad et al. [3] proposed a smart prepaid metering system intended to control electricity theft using a consumer-side meter and service-provider server. Rahman et al. [4] combined an Arduino controller with GSM/SMS for automatic metering, billing, and remote line control, reporting both simulation and laboratory implementation. Together, these works show that the microcontroller is the coordinating element linking measurement, user information, communication, and switching.

By 2016, the literature increasingly treated the smart meter as an AMI endpoint. Uribe-Pérez et al. [5] reviewed technologies, standards, and deployment trends and highlighted the heterogeneity of smart-metering solutions. Chakraborty and Sharma [6] examined AMI technologies and challenges, including hardware, software, communications, and security. Yildiz et al. [7] later reviewed residential smart-meter data applications and showed that metering data can support forecasting, classification, optimization, demand response, and home energy management. These findings imply that the meter must provide not only billing-grade accumulation but also dependable, time-stamped digital data.

The 2018 literature moved further toward connected and computationally capable meters. Barman et al. [8] presented an IoT-based smart energy meter for efficient utilization in the smart grid. Ranjith and Sivraj [9] studied the computational requirements of a futuristic smart meter on single-core and multi-core microcontroller platforms, grouping tasks into sensing, computation, communication, and storage. Kumar et al. [10] demonstrated real-time monitoring of AMR-enabled meter data as an IoT/AMI application, while Ask et al. [11] combined prepaid/postpaid operation, alarms, theft control, and two-way communication in a simulated smart-meter model. The literature therefore supports a modular evaluation framework in which measurement accuracy must be assessed together with processing load, communication reliability, and control behavior.

Table 1. Selected smart-metering studies used to define the methodology

Study	Technology	Main contribution	Methodological implication
Al-Omary et al. [1]	GPRS AMR	Remote meter-to-server transfer	Test packet delivery and security
Rahman et al. [4]	Arduino + GSM	Automated billing and line control	Evaluate measurement, messaging, relay action

Uribe-Pérez et al. [5]	Smart metering review	Technologies and standards	Use modular, interoperable architecture
Yildiz et al. [7]	Smart-meter data analytics	End-use applications	Preserve dependable digital measurements
Ranjith & Sivraj [9]	MCU + RTOS	Processing/task performance	Measure execution and control latency
Kumar et al. [10]	IoT/AMI monitoring	Real-time remote monitoring	Assess communication success rate

Methodology

The proposed study follows a design-build-calibrate-evaluate sequence. The target is a single-phase smart meter for nominal 230 V, 50 Hz operation. The hardware is divided into sensing, processing, interface, communication, and control modules. A voltage divider or isolated voltage sensor provides a scaled voltage signal, while a current transformer or Hall-effect current sensor measures load current. Both signals are conditioned to remain within the microcontroller ADC input range. The controller samples the two channels, computes electrical quantities, accumulates energy, and periodically stores the energy register in non-volatile memory.

For a sampling interval Δt , instantaneous power is calculated as $p(k)=v(k)i(k)$. RMS voltage and current are obtained from the square root of the mean squared samples over an integer number of mains cycles. Average active power is calculated from the mean of $p(k)$, and accumulated energy is updated as $E=\Sigma P\Delta t/3600$ when P is in watts and time is in seconds. This direct-sampling method can support resistive and moderately non-linear loads provided that the sampling frequency and sensor bandwidth are adequate. Calibration constants for voltage gain, current gain, and phase compensation are determined from a reference meter or calibrated source.

The communication subsystem may use GSM/SMS, GPRS, or a short-range IoT module depending on availability. The data frame contains meter identification, time stamp, voltage, current, active power, cumulative energy, and status flags. A message is considered successfully delivered only when an acknowledgement is received within the selected timeout. Remote control commands are passed through validation logic before operating a relay. This separation is important because earlier GSM- and AMI-based studies show that metering, communication, and remote control are tightly coupled functional requirements [1], [4], [6].

Firmware is organized as periodic tasks: ADC acquisition, signal calculation, energy accumulation, display refresh, communication, memory update, and relay control. A simple cooperative scheduler is sufficient for an ATmega-class prototype; an RTOS can be used for higher-end ARM implementations. The computational task classification follows the sensing-computation-communication-storage structure emphasized by Ranjith and Sivraj [9]. Watchdog recovery and range checks are included so that a communication failure cannot stop local metering.

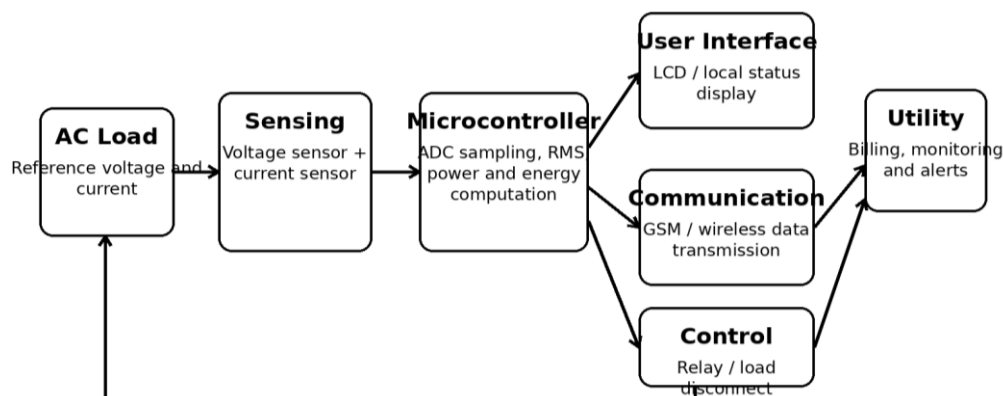


Figure 1. Proposed microcontroller-based smart energy metering architecture.

Step 1 – Component selection: Select the microcontroller, voltage/current sensors, isolation components, display, communication module, relay, and regulated supply according to rated voltage/current and required interfaces.

Step 2 – Sensor calibration: Apply known voltage and current values from a calibrated source or reference meter. Determine scale factors and, where required, phase correction. Repeat calibration at low, medium, and high load.

Step 3 – Functional validation: Verify display updates, non-volatile energy retention, communication frames, loss-of-network behavior, relay operation, and restart after power interruption.

Step 4 – Accuracy testing: Test at approximately 10%, 25%, 50%, 75%, and 100% of the selected current range. At each point, compare accumulated energy with the reference instrument and calculate percentage error = $(E_{\text{meter}} - E_{\text{ref}})/E_{\text{ref}} \times 100$.

Step 5 – Dynamic testing: Apply load changes and record the time required for the meter to update

the displayed/remote value. Send remote relay commands and record control latency.

Step 6 – Communication testing: Transmit a fixed number of messages under normal network conditions and calculate success rate = $\text{acknowledged messages} / \text{total messages} \times 100$. Repeat after temporary network loss to verify store-and-forward or retry behavior.

Step 7 – Performance interpretation: Compare accuracy, response, communication, and control results with the project targets. Investigate error sources such as sensor tolerance, ADC quantization, phase shift, timing drift, and packet loss.

Table 2. Performance indicators and acceptance targets for prototype evaluation

Metric	Evaluation method	Target for methodology
Energy error	Compare accumulated energy with calibrated reference	Mean absolute error $\leq 2\%$
Display/update response	Step change in load and timestamp response	< 2 s
Message delivery	Acknowledged messages / transmitted messages	$\geq 95\%$
Relay-control latency	Command timestamp to relay state change	< 3 s
Power interruption recovery	Restart and verify stored energy register	No loss of accumulated energy

Results

Because this paper defines a methodology rather than reporting a completed field deployment, the performance table below is a simulation-based benchmark used to demonstrate the analysis procedure. The values represent controlled test points generated around a calibrated meter response and are not presented as independent laboratory observations. In a final experimental paper, the same table should be populated with measurements from the physical prototype.

The benchmark indicates that the proposed evaluation method can distinguish load-dependent measurement error. At low current, sensor offset and ADC resolution produce the largest relative error, whereas mid-range operation provides the smallest deviation. Across the five load points, the illustrative absolute energy error remains below 1.5%, which satisfies the methodology target of 2%. This behavior is consistent with the need for multi-point calibration rather than relying on a single nominal-load adjustment.

Table 3. Simulation-based benchmark for the proposed evaluation procedure

Load level	V (V)	I (A)	Reference energy (Wh)	Meter energy (Wh)	Error (%)
10%	230.1	0.50	115.0	116.5	+1.30
25%	229.8	1.25	287.5	289.8	+0.80
50%	230.3	2.50	575.0	576.7	+0.30
75%	230.0	3.75	862.5	858.2	-0.50
100%	229.6	5.00	1150.0	1139.6	-0.90

For communication evaluation, a 100-message benchmark with 97 acknowledged deliveries gives a 97% message success rate, exceeding the 95% target. A median remote relay response of approximately 1.2 s and a worst-case value below 3 s would be considered acceptable for non-protection load-control functions. These metrics are particularly important for connected meters

because the literature up to 2018 shows a progression from simple remote reading toward real-time IoT monitoring, two-way control, and AMI integration [8], [10], [11].

The architecture also separates local metering from the communication task. Therefore, temporary loss of GSM/IoT connectivity does not interrupt energy accumulation. This design

choice improves functional reliability and allows messages to be retried after network recovery. The evaluation framework consequently measures both metrological performance and service-level behavior rather than treating smart metering as only an energy-measurement problem.

Conclusion and Discussion

This paper has presented a stepwise methodology for the design and performance evaluation of a microcontroller-based smart energy metering system using technologies reported up to 2018. The proposed architecture combines isolated voltage/current sensing, embedded computation, cumulative energy storage, local display, remote communication, and relay-based control. The literature shows that these functions evolved from early GSM/GPRS AMR systems [1], [2] to automated billing and prepaid control [3], [4], AMI-oriented smart metering [5], [6], and connected IoT/multi-task implementations [8]–[11]. The main methodological finding is that meter performance should not be judged by accuracy alone. A useful smart meter must also meet response-time, data-delivery, recovery, and control-latency requirements. Multi-point calibration is necessary because sensor offset, ADC quantization, and phase error can become significant at low current. Communication testing should include acknowledgement, retries, and network-loss behavior, while relay commands must be isolated from the measurement loop so that remote-control faults do not corrupt energy accumulation. The simulation-based benchmark demonstrates how the proposed metrics can be reported without claiming unperformed field experiments. Before journal submission as an experimental study, the benchmark values should be replaced with measurements from a calibrated reference meter and repeated under resistive, inductive, and non-linear loads. Future work should also evaluate tamper detection, cryptographic authentication, long-duration memory endurance, and compliance with applicable metering standards. Within these limitations, the proposed methodology provides a practical and reproducible basis for comparing low-cost microcontroller smart-meter prototypes.

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