Undergraduate Research and Innovation: Inexpensive Remote Campus Power Monitoring via Student Designed and Manufactured System

Peter Mark Jansson, Jeffrey Tisa, William Kim

Rowan University

Abstract

Rowan University consists of nearly forty buildings spread out over a large suburban campus. While some of the perimeter buildings are served directly from the local power company, many of the core buildings receive their electrical power from the University's 4kV grid. This grid is fed by both the local utility and an on-site cogeneration system. A recent energy study of the campus[1] revealed that the University compares poorly with peer institutions of comparable size in terms of energy efficiency because of very high electricity usage. University officials sought to sub-meter buildings with no electricity data available and found that metering equipment and installation costs were quite prohibitive. Students of the engineering department's Sustainable Design course undertook a project to develop a low cost, small, portable, easily installed solution to the problem so that the efficiency of each building could be estimated cost-effectively. The low-cost power monitoring device they designed and manufactured can store several electrical line parameters over time that will collect important energy and power characteristics of a building. The core of the device is the ADE7753 power IC from Analog Devices. It is capable of measuring instantaneous voltage and current, V_{RMS}, I_{RMS}, and apparent, real, and reactive energy. The interface to the mains of a site is accomplished with a non-intrusive flexible Rogowski Coil current sensor and voltage probe. A programmable microcontroller (PIC18F242) from Microchip communicates with the ADE7753 and retrieves the power data. Then, the data is processed by the microcontroller and saved in non-volatile memory, specifically a 64 kb EEPROM (25LC640) from Microchip. The microcontroller then reads the data from the EEPROM and transmits it to the RS232 transceiver. Once the power-monitor detects a device that is ready to receive via 9-pin RS232, it transmits the data requested from the user. Once the data is collected, it can be taken back to a computer in the Engineering Department and seen on the HyperTerminal application on a Windows platform. This significant innovation they developed with their professor is estimated to be valued at approximately $100 per unit and will likely cost significantly less in quantity. The overall market for this device are single and three-phase commercial and industrial facilities that desire energy and power quality measurements to aid them in cutting costs related to wasted electricity.

Background

As part of the Green Power Engineering pedagogy developing at Rowan University students are given the opportunity to take a senior/graduate elective entitled Sustainable Design in Engineering. The professor's website[2] contains more detailed information about the course. A key course requirement is that students undertake a project that will utilize their acquired skills to demonstrate some activity (research or technology based) that will forward the efforts of sustainable design in engineering. Co-authors Jeffrey Tisa and William Kim developed the power monitoring device described below. The device has the potential to enable universities and large campus-like commercial and industrial facilities or technology parks to better understand their power utilization without investing significant monetary and natural resources in monitoring equipment. Compared to other portable metering devices currently on the market, it contains features that are useful in gaining insight to exactly when, where, and how much power is being consumed. This is made possible by taking advantage of the latest in power metering integrated circuits, the ADE7753. Table 1 below demonstrates the uniqueness of the new meter with respect to several other specific models. In its latest version, it will be able to monitor three phase as well as single-phase power parameters.

Portable Power Meter Comparison

Manufacturer	Model #	Major Features	Data Communication	Price
Rowan University	N/A	Measures real (kWh), reactive (kVARh), apparent energy (kVAh), waveform capture, Vrms, Irms. Retains data during outage (NVRAM) Programmable recording intervals.	Yes, RS232, data download	~$100.00
Electricity Metering.com	Watts Up? Pro	Measures power, demand, peak demand, total energy used (kWh), and cost of operation for any standard 120V plug-in appliance	Yes, RS232, software included	$149.00
EZ Meter	Sequoia Plus	Accumulates kilowatt hours Data is displayed on electromechanical display.	Yes, communicates over power lines.	$177.00
Electricity Metering.com	EML-2000	Accumulates kilowatt hours on single phase 120 VAC line Elapsed monitoring (Time and Day) Selectable recording intervals Retains data during outage (NVRAM)	Yes. DL 1200 Windows software ($99.00)	$309.00 w/software

Table 1: *Rowan meter design compared to similar single phase 120 VAC meters on the market*[3-4]

Approach

The core components of the prototype meter design include the Analog Devices ADE7753 single-phase energy metering IC, Coilcraft CS60-050 air-core coil, and both the PIC18F242 microcontroller and 25LC640 EEPROM by Microchip. These particular components were chosen to keep costs low, maintain SPI compatibility throughout the device, and keep programming and implementation straightforward. The first fabricated prototype of this circuit will take advantage of a slightly more expensive current transducer, namely a flexible Rogowski Coil. The traditional Rogowski Coil is simply an "air-core" toroidal coil that is placed around a conductor to sense the alternating magnetic field that in turn induces a voltage in the coil. The majority of coils in use today are "rigid" (see Figure 1) and therefore, cannot be opened. This forces the user to disconnect the conductor (forcing a power outage at the site) and feed it through the center of the coil. This more labor-intensive application may require, in many jurisdictions, a licensed electrician and an electrical permit. In contrast, the flexible coil can be opened and wrapped around a conductor, then rejoined. This requires no interruptions in electrical service, no licensed electricians (as no circuits are opened or rewired) and no electrical permitting. This also allows the electronic metering device to be used in awkward locations that may have been previously impossible to measure. Additionally, energy auditors who are constantly monitoring power in different locations may especially find this to be an extremely powerful tool as it can readily be moved across a campus to monitor various buildings for several days at a time and develop a very good profile of what is happening without the commitment of permanently installing expensive measurement resources. In an age that is increasingly dependant on technology, power outages have become nearly intolerable. Therefore, this power monitor was designed to make its installation and removal electrically transparent to all except the user(s).

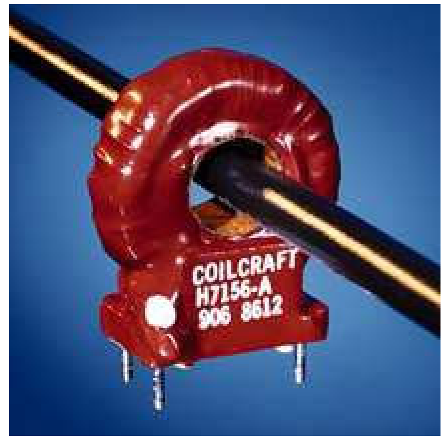

Figure 1: *Rigid Rogowski Coil*
http://www.coilcraft.com

System Development

The power meter design has revolved around low-cost and ease of use as high priorities. The components are such that all data capture and storage is done internally and currently may only be viewed through a device connected via RS-232. The device will appear as an ordinary "black box" that sits conveniently by the area to be measured. There are ports on the outside to plug in the download/programming cable and current sense coil. The metering IC is capable of capturing apparent, real, and reactive energy, as well as instantaneous and RMS voltage and current. There is even an option to reconstruct waveforms if desired. The user can choose what parameters that he/she would like to monitor by using the control interface. This product stresses the look of simplicity while providing very valuable information.

One of the innovative approaches taken with this particular design is the use of a flexible Rogowski Coil to sense current. Just like a regular Rogowski Coil, this particular product outputs a voltage directly proportional to the time derivative of AC current. According to Ampere's Law (Equation 1), the output voltage of the coil is independent of its orientation around the conductor, as long as the ends of the coil are properly rejoined[5].

$$\oint H \cos(a) \cdot dl = I$$

Where:
H = magnetic field intensity
dl = small element of length along the loop
a = angle between direction of field and direction of element

Equation 1: *Ampere's Law applied to an air-core coil*

Since the output voltage is the time derivative of the current present in the conductor with respect to time, a di/dt current sensor is needed to supplement the 90˚ phase shift and 20dB/decade gain in the frequency domain. In the past, this would cost extra money and be somewhat unreliable due to the use of analog op-amp integrators, which tend to degrade in accuracy over time[6]. The release of the Analog Devices ADE7753 Power Measurement Chip[7] has now introduced the first "meter in a chip" solution to include a digital integrator and the ability to measure reactive energy. This is a key factor in cost reduction and simultaneously allows the design to be more compact and reliable. The Rogowski Coil in conjunction with the ADE7753 presents the opportunity to manufacture a more cost-effective power-monitoring device for sub metering applications than what is currently available. As mentioned previously, the power monitoring method developed by this project (described in this paper) provides the customer with an opportunity to save money and avoid the headache of disrupting electric service, all at a projected cost of about $100.

Figure 2: *Flexible Rogowski Coil* http://www.rocoil.co.uk

At the center of the power meter is the PIC18F242 microcontroller. This particular component was chosen because it is reliable, straightforward to program, low-cost, and communicates through serial peripheral interface (SPI). It will primarily supervise the power IC, transport data, and, if desired, calculate power from the energy values stored in the ADE7753 registers. These values are gathered in the 64 kb EEPROM until downloaded by the user, upon which the EEPROM will erase the old data and begin anew. Table 2 below presents two possible scenarios. The first example shows that the system is capable of reading a real power reading once an hour for one month. The second example is the same as the latter except there are two additional parameters. Since the current EEPROM can hold 1000 32-bit values, either of

EEPROM CAPABILITIES: 64 kb (Max. of 1000 32-bit Values)

Example 1: 1 reading every 2.4 hours for 30 days with 1 parameter + date/time

Parameters	Data Capture Frequency	Total values accumulated
Real Power	10 samples/day for 30 days	300
Time of Day (HH:MM:SS)	10 samples/day for 30 days	300
Date (DD/MM/YYYY)	10 samples/day for 30 days	300
	Total EEPROM Values:	**900**

Example 2: 1 reading every 4.8 hours for 30 days with 3 parameters + date/time

Parameters	Data Capture Frequency	Total values accumulated
Apparent Power	5 samples/day for 30 days	150
Real Power	5 samples/day for 30 days	150
Reactive Power	5 samples/day for 30 days	150
Time of Day (HH:MM:SS)	5 samples/day for 30 days	150
Date (DD/MM/YYYY)	5 samples/day for 30 days	150
	Total EEPROM Values:	**750**

Table 2: *Two possible scenarios that the power meter is designed to carry out*

these two scenarios is possible. The interface to the PC will alert the user as to how long readings may accumulate in the EEPROM before space has been exhausted. This time period will depend on sampling rate, how frequently readings are taken, and the number of parameters measured. After further field-testing, if 64 kb proves not to be the optimal amount of memory for most portable applications the chip can be upgraded to what is necessary. The EEPROM is of course non-volatile and SPI compatible.

Communication between the metering circuit and the user is accomplished through a Maxim RS232 transceiver. The prototype will connect to the serial port of a PC. The Windows HyperTerminal program on a PC is the medium presently used to read incoming data. Figure 3 is a live screenshot from the initial "proof of concept" prototype. It is functioning as a Watt-hour meter. Field test prototypes however, will have the ability to connect to the serial port of a PDA for ease of data collection. Future additions to the communication aspect of the device may include USB or wireless data transfer to accelerate the data recovery process. These would be minor adjustments based off existing proven wireless data transfer technology (i.e. 802.11b/g or Bluetooth). Hardwiring the data output is being avoided to maintain the portability of the system.

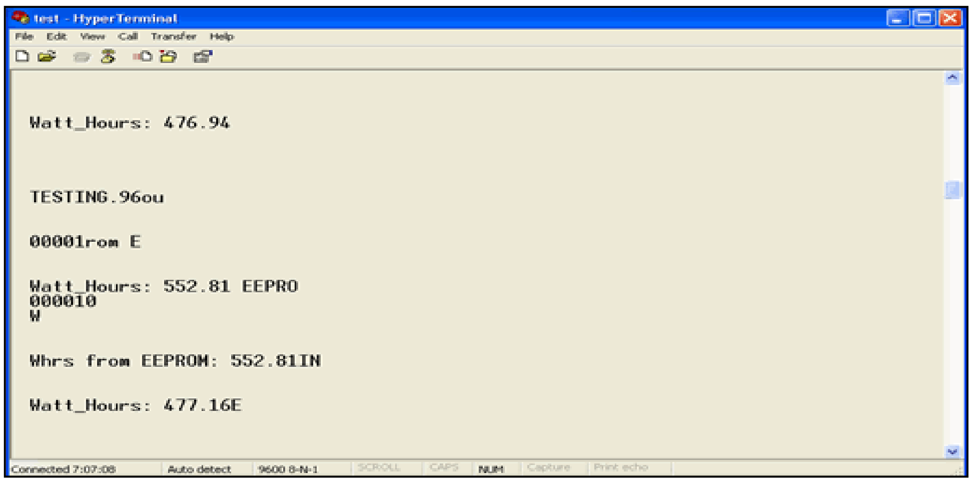

Figure 3: *Screen capture of program acquiring watt-hour readings*

Future Plans

The immediate aspiration of this project is to be able to gather power quality data at Rowan University. It will be a great help to the administration in learning how, when, and where energy can be saved. Another innovative project on sustainability education from the Rowan University Engineering Clinics[8-9] is being presented at this 2004 ASEE Conference. That paper[10] speaks of recommendations made to the University's Energy Review Panel to monitor several buildings on campus that are presently not metered use an exorbitant amount of energy that could surely be saved if the locations that waste energy can be discovered. The initial prototype meters will be suitable to monitor for approximately one month increments. They will be used in the spring of 2004 across the university campus to develop a profile of where energy can best be saved.

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Biographies

PETER JANSSON is Associate Professor of Electrical and Computer Engineering at Rowan University and leads numerous Junior Senior Engineering Clinic Teams in solving real world engineering problems each semester. He teaches Networks, Sustainable Design, Power Systems and research includes renewable power systems. He received a PhD from the University of Cambridge, MSE from Rowan University and a BSCE from the Massachusetts Institute of Technology.

JEFFREY TISA is a Masters Student in electrical and computer engineering at Rowan University and is completing his research and dissertation on "Transient Analysis of the High Pressure Sodium Lamp/Ballast System Leading to the Projection of Remaining Lamp Life," member of the IEEE Power Engineering Society.

WIILIAM KIM is a senior electrical and computer engineering student at Rowan University. In his spare time, he works part-time as an engineering intern at Chemglass Inc. in Vineland, NJ.