COTS-Based Stick-on Electricity Meters for Building Submetering

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Abstract— **We demonstrate a low-cost, 21 x 12 mm prototype Stick-on Electricity Meter (SEM) PCB to replace traditional in-circuit-breaker-panel current and voltage sensors for building submetering. A SEM sensor is installed on the external face of a circuit breaker to generate voltage and current signals at a 960 Hz sample rate. This allows for the computation of real and apparent power as well as capturing harmonics created by non-linear loads. The prototype sensor is built using commercially available components, resulting in a component cost of under $10 per SEM in moderate quantities. With no high-voltage install work requiring an electrician, this leads to an installed system cost that is roughly ten times lower than traditional submetering technology. Measurement results from lab characterization as well as a real-world residential dwelling installation are presented, verifying the operation of our proposed SEM sensor. The SEM sensor can resolve breaker power levels below 10W and consumes approximately 16 mA from a 5V supply.**

I. INTRODUCTION

Electricity usage in the USA is responsible for 40% of our primary energy expenditure and carbon emissions [1]. Commercial buildings research shows that electricity submetering combined with data analytics and maintenance follow-up can reduce a buildings electricity use by 10% to 30%; it is very likely that similar energy savings can be achieved in industrial (and possibly residential) environments [2]. However, very few buildings are outfitted with the meters required to enable these savings because of the high cost of installation. Installing a three-phase electricity meter can cost thousands of dollars because an electrician must open the electrical panel, perform hot work to install components, and install conduit and enclosures to cover the equipment and signal leads. Thus, a typical mid-size, mid-life commercial building requiring several tens of metering points can cost up to $100,000 to submeter, resulting in a payback period in excess of ten years. This large install cost is dominated by the labor required to carefully install all hardware, conduit, and wiring by highly-trained tradespeople while adhering to safety and building code requirements. In order to enable the worldwide reduction of building electricity usage, it is critical to develop electricity metering technologies that provide more granular energy information with dramatically reduced install costs.

Today's commercially available breaker panel submetering technologies require bulky current transformers (CTs) and voltage connections to be installed at every breaker. Replacing the in-panel hardware with Stick-on Electricity Meter (SEM) sensor devices on the outside of the circuit breakers provides a number of benefits. First, installation on the outside of the circuit breaker panel does not require an electrician. Second, since the system is contained between the panel face and panel door, no external wiring or conduit must be installed. These reasons, combined with lower hardware costs, pave the way for a non-contact SEM system that drastically reduces total submetering installation costs. While previous non-contact-based circuit breaker metering work has shown a current magnitude sensor with a 2 Hz sample rate, it provided no measurement of real power and required a custom MEMS fabrication process [3]. We believe that an SEM design based on commercially available components is practical for widespread adoption due to its standard PCB fabrication and assembly requirements. In this paper, we present the design of a SEM sensor PCB built using commercially available components. Our device shows very good measurement performance and can be built for a component cost below $10 in moderate quantities.

II. SYSTEM OVERVIEW

In this section, an overview of each SEM hardware subsystem and the flow of sensor data will be discussed. A block diagram of the in-panel system can be seen in Figure 1.

A. SEM Board

Each SEM sensor board is equipped with an analog front end for current and voltage signal conditioning, as well as a Texas Instruments MSP430G2131 microcontroller. Details

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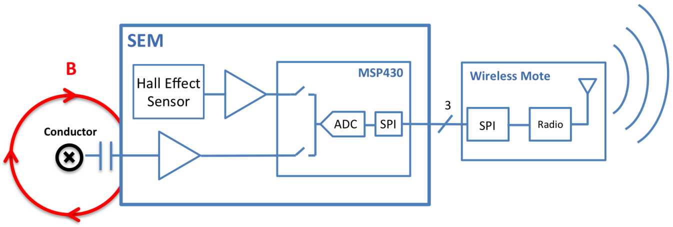

Fig. 1. SEM system in-panel block diagram showing sensing techniques, SEM, and wireless mote

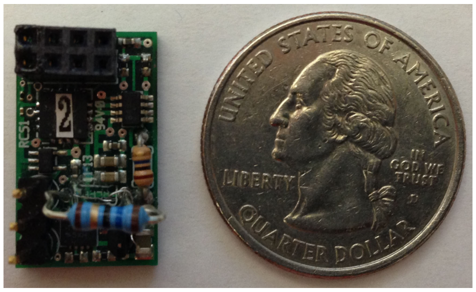

Fig. 2. 21 x 12 mm assembled Stick-on Electricity Meter with size reference

of the sensing and analog circuits will be discussed in Section III. The entire SEM board consumes around 16 mA from a 5V supply. A close-up image of the 21 x 12 mm assembled SEM PCB board can be seen in Figure 2. The SEM's microcontroller is used for two purposes in our system: sampling the analog voltage and current sense signals, and transmitting samples to the wireless mote base station via a wired bus. To preserve information in the harmonics of the sensed current signals, a 960 Hz sampling rate is used in the 10-bit microcontroller ADC. Sixteen samples (one 60 Hz cycle) of both the voltage and current sense signals are stored in the microcontroller's memory at all times. Acting as an SPI slave, the SEM's SPI interface clock is provided by the wireless mote base station. When the SEM microcontroller gets a request for data from the wireless mote, the stored samples are transmitted to the base station over the SPI bus at a 500 kHz clock rate.

B. Wireless Mote

In this system, the wireless mote [4] functions as a base station for SEM devices installed on the breaker panel. As an SPI master, the wireless mote device requests data from an SEM sensor over SPI and provides the 500 kHz clock for the SPI bus. Voltage and current samples from the SEM are then received by the wireless mote over the wired bus, and subsequently transmitted wirelessly over an 802.15.4 wireless network using the OpenWSN [5] network stack.

C. Laptop Computer

A laptop equipped with an 802.15.4 USB dongle receives wireless data transmissions from the breaker panel wireless base station, and also performs subsequent DSP computations on the received samples. Python scripts are executed on the laptop that unpack the SEM's signals and calculate parameters of interest, such as the metered breakers' line voltage signal and real power usage. This energy data can then be viewed locally in real time or sent to a web server for logging.

III. SENSING IMPLEMENTATION

A. Voltage Sensing

The analog circuits used for our capacitive voltage sensing scheme can be seen in Figure 3. The sense capacitance is essentially a parallel-plate capacitor formed between the bottom metal plane of the SEM board and the conductor in the circuit breaker. For large capacitive coupling, careful SEM board layout consideration was practiced to keep the bottom layer densely filled with metal. Assuming the sense capacitance remains constant, the capacitor current can be monitored to obtain the time-derivative of the breaker's line voltage: $\frac{dv_L(t)}{dt} = \frac{i_{sense}}{C_{sense}}$. The amplitude of this signal is controlled by the value of R_{bias} and is buffered with an opamp to drive the ADC input.

In order to calculate real power, the amplitude and phase of a monitored breaker's voltage signal must be determined. However, since the amplitude of the line voltage is fairly constant throughout a building, monitoring the amplitude of the line voltage on each circuit is not critical. The line voltage amplitude can be measured once with a multimeter at any wall outlet or simply assumed to be the specified value given the country of residence. With the line voltage amplitude known, the correct phase of the breaker line voltage must be extracted to determine the real power used by the breaker. Due to our capacitive sensing scheme, the phase of the voltage sense signal must be shifted by $+90°$ before calculating $p(t) = v_L(t) \cdot i(t)$; we have done this using a software phase-locked loop created in Python. This python script running on the laptop looks at the sense voltage output signal from the SEM board, estimates a best-fit sinusoid, and then shifts this signal by $+90°$. This synthesized phase and amplitude correct line voltage signal is used in subsequent real power calculations.

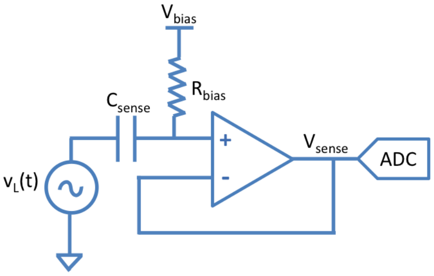

Fig. 3. SEM board voltage sense circuit analog front end

B. Current Sensing

At the heart of our current sensing scheme is a hall effect sensor that detects magnetic fields generated by currents flowing through a metered circuit breaker. The sensor used in this work is an SIP package A1301 Hall Effect Sensor by Allegro MicroSystems, with a 2.5 mV/Gauss sensitivity. A diagram of the current sensing analog circuitry is shown in Figure 4. Since the output of the hall effect sensor is single-ended, a reference needs to be generated for the instrumentation amplifier's inverting input. To create this reference, the output of the hall effect sensor is averaged by the low-pass filter formed with components R_1 and C_1. The amplified current sense signal is then passed through the R_2C_2 anti-aliasing filter for sampling by the microcontroller's ADC.

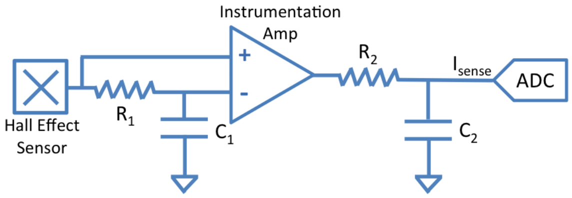

Fig. 4. SEM board current sense circuit analog front end

IV. Experimental Results

In the characterization of our SEM prototype, measurements were completed in a laboratory environment as well as in an actual residential installation. Figure 5 shows the internals of a common residential circuit breaker with a bimetallic strip trip mechanism. From our investigations, most thermal and thermal-magnetic breakers have very similar internal geometries and current paths. It is important to note that the breakers tested in this work do not contain solenoids for electromagnetic actuation, which would increase the magnetic field magnitude around the breaker by 10-20x. If solenoidal breakers were to be considered, the design of a high resolution current sensing system would be much easier due to the drastically increased SNR. For this work, we focused on the more challenging but also much more prevalent thermally (thermal-magnetic) actuated circuit breakers.

Fig. 5. Biimetallic strip circuit breaker innards with SEM annotated.

A. Laboratory Evaluation

To characterize the response of our SEM sensor, its voltage and current sense outputs were monitored across a wide range of load currents; the test setup will now be described in detail. Our SEM device was powered by a 5V DC power supply and mounted onto the face of a circuit breaker in a bench top breaker panel. The bench top breaker panel is powered with a standard US power plug, which was plugged into the wall through a 20A power meter to provide reference power measurements. Lightbulb loads of various power ratings were switched on to load the breaker with different current magnitudes. The SEM voltage and current sense signals were sampled with 16x averaging by an oscilloscope and subsequently processed in software to calculate real power. Figure 6 presents the results of this experiment, comparing the output of our SEM sensor with the reference power meter. In this plot, the y-axis is a log scale, and measurement errors are less than 1% of full scale (1 kW) and typically less than 2% of measurement. From this plot, it is apparent that our sensing technique is very effective, showing strong correlation with a reference meter down to load power levels below 10W. Using this same test setup, we also monitored the outputs of our sensing system with a non-linear, TRIAC dimmer load. The time-domain waveforms from this measurement are shown in Figure 7, including the synthesized, phase-corrected line voltage signal.

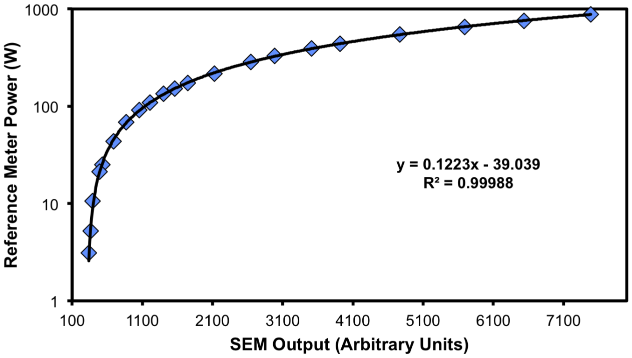

Fig. 6. SEM output vs. reference plug-through power meter, showing great correlation to sub-10W load powers

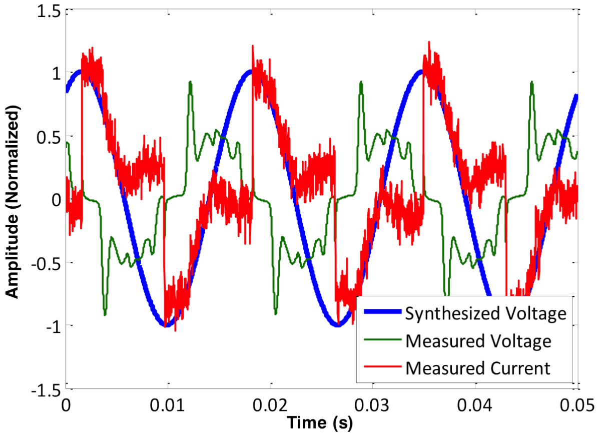

Fig. 7. Measured and synthesized SEM waveforms for TRIAC dimmer load

B. Residential Installation

Our SEM system was installed on a breaker in a home to test the sensor in a real-world environment with various load types and transients. The breaker panel used for this test was also outfitted with a TED 5000 whole house meter, serving as an accurate reference for calibration and measurement validation. During this experiment, the SEM and wireless mote were powered by a 5V DC power supply plugged into a wall outlet near the circuit breaker panel. Figure 8 presents a photo of the hardware installed in the circuit breaker panel. A laptop receiving 802.15.4 wireless SEM sensor data, executing Python DSP software, and uploading data to an SMAP server [6] was placed in a room adjacent to the breaker panel.

The SEM was installed on the dwelling's kitchen circuit, which contains multiple appliances. Calibration of the sensor was completed by plugging different resistive loads into a kitchen wall outlet (with other loads static), and monitoring changes in the output of the SEM and TED meter. This established a calibration coefficient mapping the SEM's output to real power values. The coefficient was then programmed into the laptop's python script for subsequent logging of real power data. A plot of the power data from both the SEM-metered kitchen circuit and the reference TED meter over a period of 8 hours is shown in Figure 9. It can be seen that the SEM sensor is accurately measuring power for loads with non-unity power factor. Differences in the trends of the two curves shown are due to load changes on other circuits in the residence.

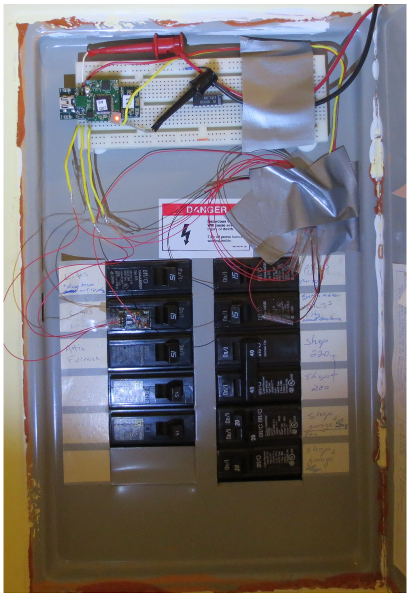

Fig. 8. SEM system installed in residential breaker panel. Wireless mote in breadboard at top of panel and SEM installed on kitchen circuit breaker

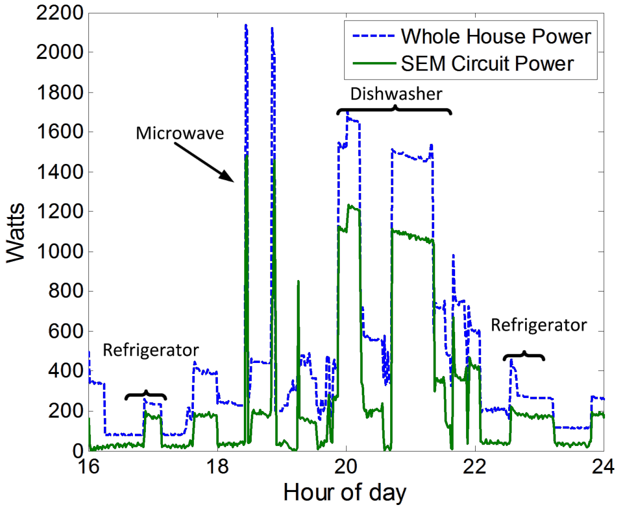

Fig. 9. Whole house and kitchen circuit SEM meters' 8-hour energy data

V. CONCLUSION

We have presented a new sensor system for building sub-metering at the circuit breaker panel that solves many issues inhibiting the widespread adoption of current technologies. Our solution includes cost effective hardware that is suitable for installation without an electrician, and is easy to produce without an exotic manufacturing process. We estimate the installed cost of our system to be roughly 10 times lower than other available solutions. Through the measurements presented in this paper, we have shown that our sensor accurately measures real power and works well in a residential installation with various types of loads. We believe the fundamental limitation in this system is due to the commercial hall effect sensor SNR at the magnetic field strengths of interest, introducing a measurement resolution vs. update frequency tradeoff. Future work in this area will include full panel submetering, as well as a self-calibrating SEM system.

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REFERENCES

[1] Energy Information Agency, *Annual Energy Outlook 2012 Early Release*, www.eia.gov/forecasts/aeo/er/.

[2] National Science and Technology Council Committee on Technology, Subcommittee on Buildings Technology Research and Development, *Submetering of Building Energy and Water Usage*, 2011.

[3] Q. Xu, M. Seidel, I. Paprotny, R. White, and P. Wright, "Integrated centralized electric current monitoring system using wirelessly enabled non-intrusive ac current sensors," in *Sensors, 2011 IEEE*, 2011, pp. 1998–2001.

[4] A. Mehta and K. Pister, "WARPWING: A complete open source control platform for miniature robots," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, 2010, pp. 5169–5174.

[5] T. Watteyne, X. Vilajosana, B. Kerkez, F. Chraim, K. Weekly, Q. Wang, S. Glaser, and K. Pister, "OpenWSN: a standards-based low-power wireless development environment," *Transactions on Emerging Telecommunications Technologies*, vol. 23, no. 5, pp. 480–493, 2012.

[6] S. Dawson-Haggerty, X. Jiang, G. Tolle, J. Ortiz, and D. Culler, "sMAP: a simple measurement and actuation profile for physical information," in *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, ser. SenSys '10. New York, NY, USA: ACM, 2010, pp. 197–210.