ENERGY SUBMETERING FOR CIRCUIT BREAKER PANELS USING MEMS OR MESOSCALE PASSIVE PROXIMITY CURRENT SENSORS

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Abstract: This paper presents a novel, non-intrusive method of monitoring electrical energy usage in residential and commercial environments. Our newly developed wirelessly enabled MEMS/Mesoscale AC current sensors are attached to existing circuit breakers to enable the use of circuit breaker boxes as centralized locations for monitoring power usage. The previously presented MEMS [1] and mesoscale current sensors (Fig. 1 & 2) are able to couple to the magnetic fields generated by the AC currents in the circuit breakers, producing an electrical signal that is proportional to the AC current. Both FEM analysis and experimental results revealed a “hot spot” on a typical circuit breaker where the maximum coupling is achieved. At that location, the mesoscale current sensor exhibits a sensitivity of 61.8 mVrms/A rms, and is able to harvest 20 µW of energy. Some commercially available low-powered radio motes equipment permit wireless real-time monitoring of individual circuit breakers to aid in retrofitting legacy buildings and improving the efficiency of electric energy usage.

Keywords: Demand response, AC current sensor, circuit breaker, legacy building, wireless sensor network.

INTRODUCTION

The Demand Response (DR) initiative is based on automated load reductions through dynamic energy pricing and real-time monitoring of electrical energy usage. Realization of DR requires low-cost, durable and self-powering wireless sensor networks to be deployed in accessible and centralized locations. Multiple current sensing technologies, including shunts, current transformer, Rogowski coil [1], Hall effect sensor and others, have been developed over the past few decades. However, among all of these technologies, few meet the requirements of being non-intrusive, self-powering, low cost and having small footprints at the same time. Our recent research effort has been focused on designing such current sensors that satisfy these criteria. As a result, a MEMS/mesoscale piezoelectric AC current sensor has been developed [2].

In this work, we are deploying these electric current sensors on existing circuit breaker panels in a legacy building to monitor its power usage (Fig.3). The sensors are attached on the breaker with a double-sided tape and connected with a radio mote that sends current readings wirelessly to a laptop. The sensors are then calibrated by adding a constant load to a circuit that is being monitored and observing the sensor’s voltage increment caused by the current used by that additional load. This experiment has successfully demonstrated that the circuit breaker panel is an ideal centralized and accessible location for power monitoring in the commercial and residential area. It also shows that our newly developed current sensor is capable of providing reliable electric current measurement without modifying any components of the existing power delivering systems.
2. THEORY

2.1 Linear voltage response

The mesoscale electric current sensor is constructed from a bimorph piezoelectric cantilever (Q220-A4-203YB, Piezo Systems) with two permanent magnets mounted on its tip (Fig. 1 & 2). In recent study, we observed that our piezoelectric sensor responded linearly to the driving current only when its resonance frequency differs from the driving frequency (AC current). When the resonance frequency was near the driving frequency (AC current) a softening type nonlinear behavior was observed [3]. The same phenomenon of such nonlinearity for a multilayer piezoelectric cantilever has been reported by many other researchers over the past few years [4, 5, 6]. Thus, the purpose of this linearity analysis is to understand at what operating conditions, the electric current sensors will exhibit linear behavior as desired in the sensing application.

The sensor’s response to the AC current can be regarded as a conservative single degree of freedom system, which is described as a second-order differential equation with a softening type nonlinear restoring term [3, 7],

\[
\frac{d^2 V}{dt^2} + \omega_r^2 V - \varepsilon I_o \cos(\Omega t) = \kappa I_o \tag{1}
\]

where \( V \) is the output voltage, \( I_o \) is magnitude of the driving current, \( \kappa \) is the effective coupling constant, \( \omega_r \) is the resonance frequency, \( \Omega \) is the driving frequency of the AC current and \( \varepsilon \) is a positive measure of nonlinearity which is determined empirically. Using the Poincaré–Lindstedt perturbation method, this nonlinear equation can be solved and the following relationship is obtained [7],

\[
\frac{3}{4} \varepsilon V_o^3 + (\Omega^2 - \omega_r^2) V_o = \kappa I_o \tag{2}
\]

where \( V_o \) is the magnitude of the output voltage. Therefore, \( \varepsilon \) can be experimentally determined by setting the driving frequency equal to the resonance frequency (\( \Omega = \omega_r \)) and observing the voltage vs. current response,

\[
\varepsilon = \frac{4 I_o}{3 V_o^3} \tag{3}
\]

Therefore, through differentiating Eq. 2, we know that the voltage response depends linearly upon input current only when the following condition is satisfied,

\[
\Omega^2 - \omega_r^2 \gg \frac{9}{4} \varepsilon V_o^2 \tag{4}
\]

Eq. 4 evaluates the operating conditions and helps us to determine whether the sensor is being driven at its linear regime.

2.2 Magnetic field distribution on the surface of a circuit breaker panel

The electric current sensor is driven by the magnetic force produced by the AC electric current flowing inside the circuit breaker. The coupling force is proportional to the integral of the field gradient over the magnet’s volume [2]:

\[
F = B_r \int \frac{d}{dy} (H_y) dV
\]

where \( B_r \) is the remanent flux density of the permanent magnet, \( F \) is the force on the magnet and \( H_y \) is the components of the magnetic field normal to the exposed surface of the breaker.

The magnetic field gradient on the surface of a typical circuit breaker used in commercial and residential buildings was investigated in order to find out where the maximum coupling strength is achieved. We built a finite element model based on the internal structures of this circuit breaker. The simulation results from that model revealed a ‘hot spot’ (Fig. 4 (a)) where the maximum field gradient is located. This numerical data agreed with our experimental results very well. The maximum voltage response (Fig. 4 (b)) was found at the same location as indicated by the numerical simulation. Therefore, the sensors are installed such that the magnets are located at those “hot spots” on the breakers.
3. FINDINGS

3.1 Frequency response

Fig. 5 shows the frequency response of the piezoelectric current sensor’s tip deflection. The current sensor was driven by a nearby energized conductor. The frequency of the current passing through that conductor was gradually increased from 55 Hz to 103 Hz. The tip deflections at different frequencies were measured using a reticle on a microscope. The resonance frequency was tuned to 81 Hz so that it is off the 60 Hz driving frequency in order to produce the linear voltage response. From Fig. 5, we also determined the quality factor and the damping ratio of our sensor to be 18 and 0.028, respectively.

3.2 Sensitivity and resolution

Fig. 6 shows the voltage response of our mesoscale current sensor installed at the “hot spot” of the circuit breaker. The sensor was tuned to 81 Hz while being driven at 60 Hz. When the AC current was increased from 0 to 17 A$_{rms}$, the current sensor exhibits a linear behavior with a sensitivity of 61.9 mV$_{rms}$/A$_{rms}$. The uncertainty of the current measurement was mainly attributed to the ambient electric noise being picked up by the sensing circuitry and the ambient vibration sources. According to our observation, the overall noise was about 10 mV$_{rms}$. Therefore, the resolution of the current measurement was determined to be ±0.17 A$_{rms}$.

3.3 Energy scavenging

We also investigated the possibility of using our electric current sensor as an energy scavenger to power the signal conditioning circuit and the radio motes. With 12 A$_{rms}$ of AC current passing through the circuit breaker, our sensor is able to generate 22 $\mu$W at 1 M$\Omega$ of resistive load (Fig. 7). One TI radio mote (EZ430-rf2500) (Fig. 8) has 10 analog inputs that allow it to sample data from multiple current sensors at the same time. That means the energy scavenged from ten current sensors can be used to power one radio mote. Knowing that the radio mote consumes 20 mW when it is transmitting or receiving data and for the rest of time, it goes to sleep mode where it only use 4 $\mu$W [8], we can achieve a 1% duty cycle without using any batteries.
DISCUSSION
The advantages of installing our passive proximity-based current sensors on the circuit breaker panels to monitor the electrical power usage are:

- The sensor is a standalone device which does not need an additional power supply.
- The non-intrusive feature greatly reduces the cost of installation.
- The small footprints of our MEMS [2] and mesoscale sensors (Fig. 3) allow them to be installed in the limited space in the panel box.
- As the circuit breaker is a centralized and accessible location for current measurement, it provides the possibility of using RFID technology for data inquiry.

However, there are also some problems that need to be addressed in our future work. For example, the current sensors are subject to the vibration shock damage and their measurements will be interfered by ambient vibration sources. A soft stopper using a series of hardening springs is proposed to protect the piezoelectric cantilever against mechanical damage. Since the frequency of the transient response excited by the external vibration is equal to the natural frequency. We are testing a band-pass filter that attenuates all frequencies other than the AC driving frequency to ensure high quality of performance. Incidentally, initial fatigue testing results show no significant voltage fluctuations over $10^7$ vibration cycles. Continuing analysis and experiment will be conducted to further determine the fatigue characteristics of a bimorph piezoelectric cantilever under weak excitation.

CONCLUSION
We have successfully demonstrated that our AC electric current sensor is able to provide reliable electric current measurement from the circuit breaker panels in commercial and residential buildings. Our sensor exhibits a sensitivity of 61.9 $mV_{r.m.s.}/A_{r.m.s.}$ at the location where the maximum magnetic coupling strength is found. A linearity analysis has been performed to determine under what operating condition, the sensor’s behavior respond linearly with the AC current variation. The AC current sensor is able to generate 20 $\mu W$ from the circuit breaker when driven by 20 $A_{r.m.s.}$ of AC current.

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