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“Stethoscopes” for Nonintrusive Monitoring

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***Abstract*—This paper provides a survey of example sensors that can be implemented with nonintrusive electromagnetic measurements. Stray electric and magnetic fields exist around many important components in commercial and industrial processes. For example, power cables operate surrounded by magnetic and electric fields. Flow meters operate with cyclically-varying magnetic fields. And stray electromagnetic fields can serve as an energy source for powering sensors wirelessly. These stray fields provide remarkable opportunities for nonintrusive sensing of industrial processes. Sensed information can be used to establish monitoring in new or retrofit systems, or can be used as a backup or redundant source to verify the operation of an installed sensor network. Three different example sensors are presented in this paper for power monitoring, fluid flow tracking, and electromechanical vibration monitoring. All three sensors make use of a common set of circuits for electric and magnetic field sensing. They illustrate approaches that could be applied for many other sensing applications.**

I. INTRODUCTION

We live in a remarkable time, when an extraordinary array of inexpensive sensors are available for measuring magnetic and electric fields. These sensors are cheap, monolithically integrated devices. They can be applied to make measurements in unconventional ways that simplify the problem of gathering information in environmentally challenging situations where maintaining the integrity of electrical isolation, or fluid or gas containment, is desirable. To apply these sensors, advanced signal processing may be required. The rapid explosion of low-cost computing in portable packages allows us to apply new sensor packages in unconventional ways.

This paper presents a survey of techniques for detecting and using stray magnetic and electric fields to sense currents, voltages, fluid flows, and vibration. Other applications, for example, thermal monitoring, are possible and have been demonstrated. The paper begins with a review of a techniques for nonintrusive electrostatic and magnetostatic sensing. These electric and magnetic sensors provide electronic “stethoscopes” for “listening in” on the physical processes associated with electromagnetic energy conversion. Then, the paper reviews applications of these techniques for electrical current and power monitoring, fluid flow monitoring, and condition monitoring for electric machinery.

II. “STETHOSCOPES”

With careful circuit design and signal processing, voltages and currents in a target system can be determined through thoughtful signal processing and analysis of stray electric and magnetic fields.

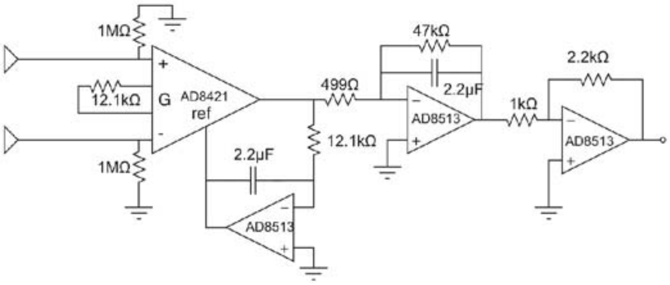

Fig. 1. Non-contact voltage sensor schematic.

A. Non-contact Voltage Sensing

A capacitive pickup can be used to sense electric field in order to determine voltage without making an ohmic contact. By measuring the voltage this field induces on the pickup, it is possible to calculate the voltage of the conductor itself. A non-contact voltage sensor schematic is shown in Fig. 1. The differential inputs to the instrumentation amplifier are connected to two copper foil plates which serve as capacitive pickups. The $1\text{M}\Omega$ resistor provides input bias current to the amplifier while maintaining the high impedance required to build up voltage on the pickup due to the surrounding field. This input stage forms an RC divider with a transfer function of

$$H(s) = \frac{sRC}{1 + sRC} \tag{1}$$

While the resistance is high, on the order of the bias resistor, the capacitance is very small, estimated to be on the order of a few picofarads, so the quantity $sRC \ll 1$, and the transfer function reduces to sRC. In order to compensate this undesired frequency response, the instrumentation amplifier is followed by an integrator. As with the non-contact current sensor, any DC offset leads to saturation at the gain stage so the same feedback technique is used to remove any differential mode DC offset between the pickups. The final stage is a standard inverting amplifier.

The electric field can be measured using a single-ended topology but a differential design increases the performance with minimal increase in complexity. In an environment with many different high voltage conductors, a single foil pickup acts as an omnidirectional sensor. By using a differential

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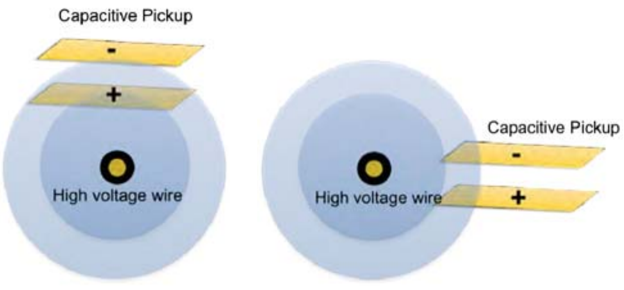

(a) Differential mode (b) Common mode

Fig. 2. Differential design concentrates the gain below the sensor

setup the sensor can be directionally targeted to the region of interest. Figure 2 illustrates the differential sensor operation. Conductors directly below the sensor generate higher magnitude fields on the bottom plate than on the top plate while conductors to the sides of the sensor generate equal magnitude fields on both plates. The differential amplifier rejects the common mode signals providing selectively higher gain to conductors located below the sensor surface. See [1] for additional analysis of the sensor operation. Also, digital implementations of the integrating filter and the advantages of an additional shielding plate are considered in [2].

In addition to increasing the positional sensitivity of the device, the differential input also attenuates the sensitivity to weak fields in the environment. This can be understood by considering the magnitude of the electric field at the sensor plate in terms of charge on the conductor of interest. The electric field is described by Coulomb's law where q is the charge on the conductor and r is the distance from the conductor to the sensor plate:

$$|E| \propto \frac{q}{r^2} \tag{2}$$

For the differential circuit the two plates are stacked vertically, and assuming a unit distance between the plates, the output of the sensor becomes

$$\begin{aligned} S_{diff} &= |E_+| - |E_-| \\ &\propto \frac{q}{r^2} - \frac{q}{(1+r)^2} \end{aligned} \tag{3}$$

The differential topology reduces the pickup of extraneous electric fields which significantly improves sensor operation in environments with unwanted pick-up, e.g., from 60 Hz sources.

B. Non-contact Current Sensing

Ampere's Law establishes the relationship between magnetic fields and current. However, without a closed magnetic path around the conductor, accurately measuring this magnetic field is a challenging task. On the exterior of a power cable with multiple conductors, the magnetic fields are not necessarily uniform or symmetric, and depending on the particular geometry, can be very small – less than 1 Gauss for bench top load currents in typical wires. We review two circuit topologies that can accurately sense these small fields and can do so even in the presence of DC offsets introduced by nearby magnetic elements.

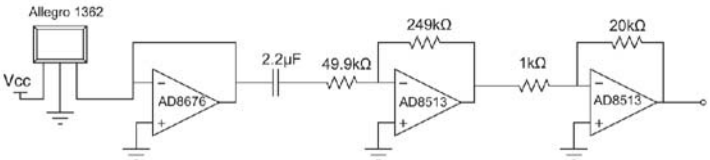

Fig. 3. Schematic of Hall Effect-based current sensor.

The first circuit, based on a Hall Effect sensor, is a cost effective solution suitable for measuring larger loads or in situations where the wire topology exposes a relatively strong magnetic field. The second non-contact circuit uses a Tunneling Magnetoresistive (TMR) element (a recently introduced sensor technology [3]) with an inductive feedback technique to accurately measure very small fields.

1) Hall Effect Sensor: The schematic for this circuit is shown in Fig. 3. The Hall Effect is widely known and used in many current sensor designs. A sensitive device available in quantity is Allegro MicroSystem's A1362 Hall Effect sensor [4]. The A1362 has a programmable gain which can be set up to 16 mV/G, sufficient to resolve the magnetic fields around a standard power line, for example. In order to measure small fields without saturating the output, we add a high pass filter with a cutoff at 1.5 Hz to AC-couple the sensor to the inverting amplifier gain stage. The large capacitive input of the filter stage requires a follower to buffer the sensor output. Overall gain can be adjusted by tuning the feedback leg of the gain stage.

In situations where the geometry of the fields is approximately known, the response of the Hall Effect circuit can be improved by attaching magnetic material parallel to the field lines around the A1362 chip. Alternatively, the sensors are sufficiently sensitive that they can be used in "free space" around typical conductors to sense fields. Figure 4 shows a collection of four sensor heads, with a close-up of a Hall sensor in the inset image. The sensor board shown in the inset includes a Hall sensor, and also a capacitive plate for voltage monitoring. The board fits in a plastic housing that includes a permalloy shield to minimize interference from magnetic sources other than the monitored cable.

2) Tunneling Magnetoresistive Sensor: The TMR effect describes the change in resistance of a particular material due to applied magnetic fields. An explanation of the effect was first published in the 1970's but garnered little interest because practical implementations generated relatively small changes in material resistance [5] . Recent advancements using new materials and advanced fabrication techniques have improved the sensitivity of TMR devices. Modern state of the art sensors have a tunnel magnetoresistance of over 600% at room temperature [6], [7]. Interest in these devices has increased as they have become integrated into high density magnetic disk drives and MRAM [8].

The STJ-340 is a TMR Wheatstone bridge sensor produced

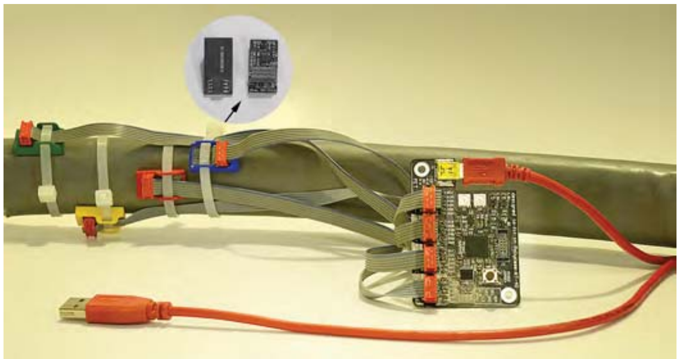

Fig. 4. Multi-conductor cable monitored by combined Hall current sensors and capacitive voltage sensors.

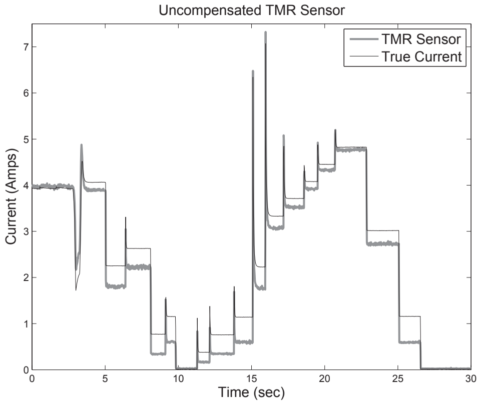

Fig. 5. Non-linear response of an uncompensated TMR-based sensor. The sensor does not have a consistent response to a given change in current.

by MicroMagnetics. The sensor has four active TMR elements, arranged in a Wheatsone bridge architecture. Changes in the field induce an imbalance in the bridge which can be measured by a differential amplifier [3]. While the STJ-340 can detect very small fields (25mV/G as constructed), there are two significant challenges in using it as a current sensor. First, as with the Hall Effect-based sensor, DC offset errors quickly saturate the sensor output. The offset errors from the environment and from imbalance in the bridge itself (which can be up to 10%) must be removed before applying any significant gain to the output. More troubling is that the TMR sensor's response to large changes in magnetic field is inconsistent and non-proportional; that is, there is no constant ratio between the change in the magnetic field and the resulting change in the sensor output. The sensor's nonlinear response to large changes in the applied field. Figure 5 compares the true current as measured by a commercial current sensor (an LEM LA-55-P) to the output of an uncompensated TMR-based sensor. Even with proper amplification and DC offset removal, step changes in the load current produce non-linear responses in the sensor output.

The circuit shown in Fig. 6 addresses both the DC offset and the non-linearity problems of the TMR sensor. The DC offset error is corrected by an integrator connected to the REF pin of the instrumentation amplifier. Any DC component is subtracted off the amplifier output resulting in a purely AC signal. This output is then fed through a high gain stage which drives an air core solenoid wrapped around the STJ-340. The current through this solenoid builds a magnetic field that opposes the applied field, creating a feedback loop that zeros the operating point of the STJ-340. Keeping the sensor element exposed to very small fields improves the sensor linearity and increases its range of operation. The current driven in the compensation solenoid is sensed as a voltage across a 150Ω resistor. The final stage is a high pass filter and gain stage that removes any offset not compensated for in the integrator.

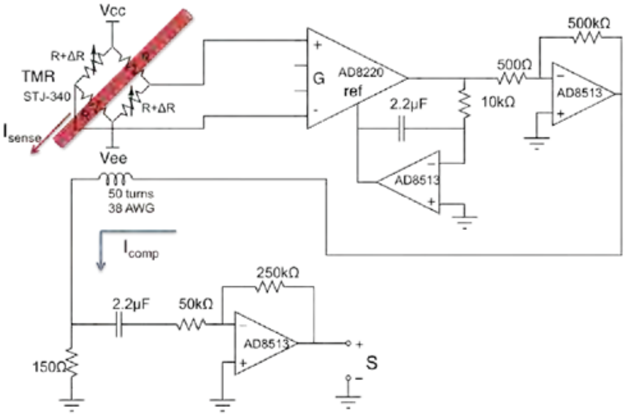

Fig. 6. Schematic of the compensated TMR-based current sensor

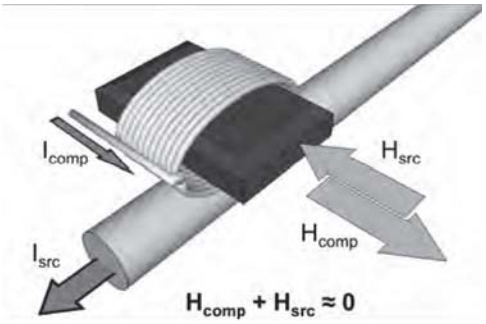

Fig. 7. Illustration of TMR feedback technique

The conceptual operation of the feedback topology is shown in Fig. 7. In steady state operation the sensed H_{src} and driven H_{comp} fields are approximately equal and the TMR element is exposed to only a very small residual field. The air core solenoid has proven remarkably effective because closed-loop feedback is used to control the compensation coil.

These "stethoscope" sensors can be combined in creative ways with other circuitry to create a huge array on nonintrusive monitoring systems for different applications. The next three sections discuss illustrative examples.

III. POWER MONITORING

The magnetic field "stethoscope" can be used to monitor the currents in a multi-conductor cable as illustrated in Fig. 4. For example, for a cable with several line currents and a neutral return,

For example, for a three phase power cable, there might be three line currents and a return for a total of four current carrying wires. With four magnetic sensors placed around the cable, a the full matrix relating the four sensor measurements to the four currents has 16 elements. However, Kirchoff's current law reduces the number of unknown currents by one. A nine element matrix using only three sensors is enough to determine all the currents. The equations to determine the currents I_k in a three-phase power cable from three magnetic field sensor measurements S_k are:

$$\begin{aligned} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} &= \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix} \times \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \qquad (4) \\ I_{neutral} &= -(I_1 + I_2 + I_3) \end{aligned}$$

The "fit matrix" $[K]$ can be determined using a calibration procedure described in [9]. By applying the fit matrix $[K]$ to sensed magnetic field measurements S_k, the non-contact sensors accurately measure the true current waveforms in each line. Figure 8 compares the envelopes of reconstructed real power from the "stethoscopes" measuring current and voltage compared to the real power measured with a conventional wattmeter using LEM LA-55-P current and LV-25-P voltage sensors.

IV. FLOW MONITORING

The high sensitivity of the compensated TMR circuit makes it useful for applications outside of power monitoring. For example, the sensor can be used to measure water flow rate by retrofitting it onto a commercial utility water meter. These utility water meters are inexpensive (usually less than twenty dollars at retail prices) and designed to last. They are essentially "odometers," and they do not inherently provide detailed flow information.

The majority of utility water meters share a common core design. A solid brass enclosures with a positive displacement cup spins as water flows through the meter. As shown in Fig. 9, the displacement cup has a magnet on its axle that couples to a similar magnet on the billing hardware outside the brass enclosure. Using magnets instead of a mechanical coupling ensures the structural integrity of the pipe and reduces the chance for leaks.

The magnetic field at a fixed point on the periphery of the water meter is a function of the rotation angle θ of the magnets inside the meter. Assuming an accurate meter with no internal leaks, θ will depend on the total volume of fluid that has passed through the meter. Total volume metered after an arbitrary starting point is the integral of the flow rate over the same period, relating $\theta(t)$ to flow rate $f(t)$.

The flow rate $f(t)$ is related to the derivative of the phase of the harmonic components of the observed magnetic field $H(t)$. For a mono-component analytic signal, the instantaneous frequency (IF) is the instantaneous phase derivative, and many algorithms for estimating IF from analytic signals may be employed to deduce instantaneous flow rate. Because flow does not always occur, the signal in question may have extended periods of low frequency or dc operation. We therefore require two magnetic sensors, mounted with circumferential separation, to serve as a "stethoscope" to produce a second real valued signal. We also require an angular correction scheme to combine the two real valued signals into a suitable analytic signal for IF estimation. Using two TMR sensors also allows flow direction determination.

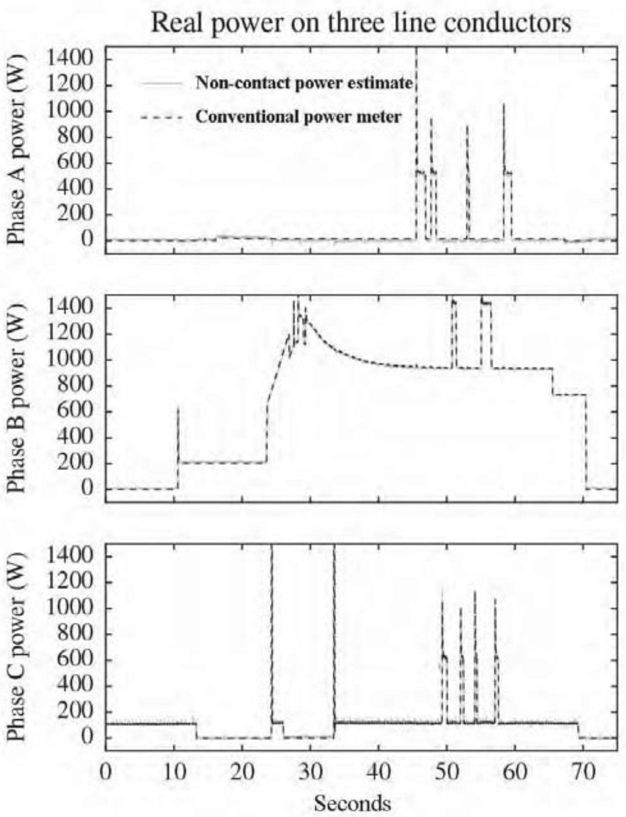

Fig. 8. Power measured with non-contact "stethoscopes" for current and voltage compared to conventional intrusive power measurements.

The TMR sensors measure the small magnetic fields that escape the meter enclosure. The frequency of oscillation is proportional to the flow rate of the water. Unlike current signals which are fixed at the line frequency (50 or 60 Hz), the frequency of the field generated by the meter varies from zero up to the maximum pipe flow rate. The feedback design in the compensation circuit eliminates low frequency components of the magnetic field. By adding an additional output from the `ref` pin of the instrumentation amplifier shown in Fig. 6, these low frequency components can be recombined with the sensor output in software. The full signal processing for this application is described in [10]. The complete prototype is shown in Fig. 10.

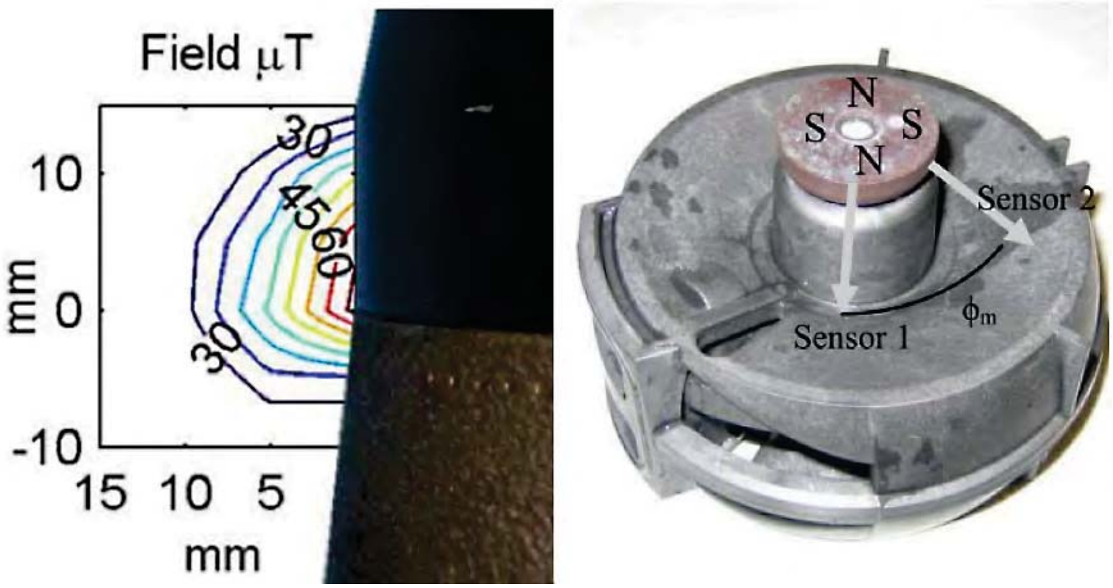

Fig. 9. Utility water meter: internal paddle wheel couples magnetically to billing hardware outside the watertight enclosure.

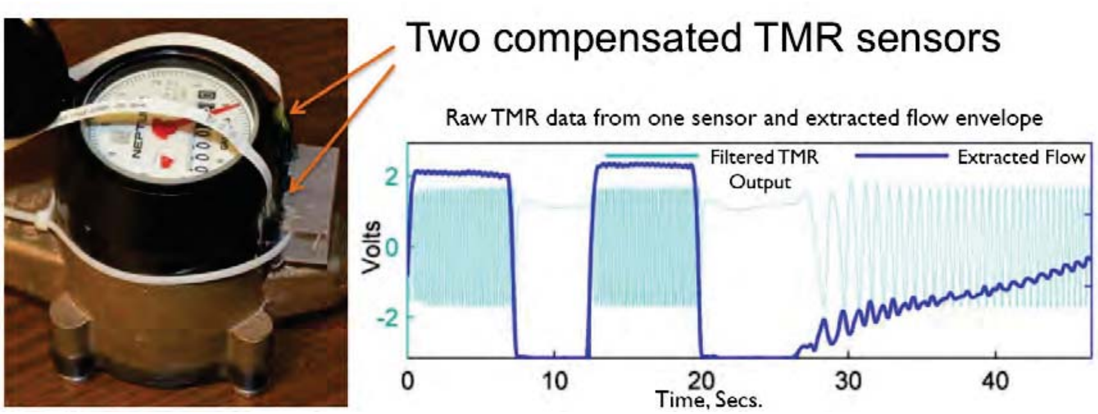

Fig. 10. Retrofit flow meter using compensated TMR sensors.

V. MECHANICAL CONDITION MONITORING

We are developing a retrofit self-powered sensor (RSS) configured for automated condition monitoring of resiliently mounted machines, e.g. motors in industrial and refining operations. The sensor package is installed mechanically in the terminal wiring box of an electric machine of interest. The RSS package harvests energy from the magnetic fields around a monitored power wire. The sensor nonintrusively detects the start of a machine's spin-down, e.g. when a seawater pump turns off, via an abrupt change in current in the machine's power wiring. An accelerometer is used to collect vibration data during the spindown. The "capacitive stethoscope" or voltage sensor can be used to collect back-EMF voltage data before and after the spin-down event.

The RSS digital sensor package consists of microcontrollers, a 3-axis accelerometer, a temperature sensor, a back-EMF sensor, data storage devices, a real-time clock, and wireless communication devices. The data storage devices include two Ferroelectric RAMs (FRAM) and one SD card. The wireless communication devices include a Bluetooth Low Energy (BLE) module and a WIFI module. The accelerometer and the back-EMF sensor are sampled at $2\,\mathrm{kHz}$, and the temperature sensor is sampled at $20\,\mathrm{Hz}$. The accelerometer measures the vibration of a motor, from which a relative vibrational energy is inferred. The back-EMF sensor measures the back-EMF voltage appearing across the phase wires of an electromechanical machine when the machine is spinning down. This back-EMF voltage data is used to infer the rotational speed of the machine during the spin-down. Figure 11 illustrates a prototype unit before installation in the control box of a motor, compared to a US one-cent coin. The physical size is approximately $54.28\,\mathrm{mm} \times 54.28\,\mathrm{mm} \times 23.2\,\mathrm{mm}$.

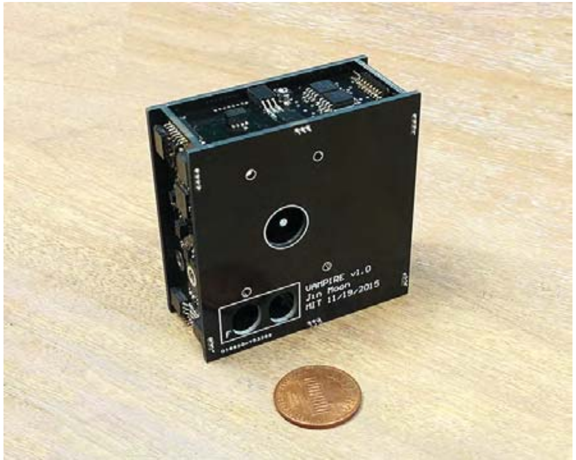

Fig. 11. Retrofit vibration sensor.

Even when the motor is technically “off” and disconnected from the utility and spinning down, the rotor retains residual magnetic field. This field generates a back-EMF whose amplitude and frequency vary with speed as the machine slows. The capacitive voltage sensor therefore becomes a nonintrusive speed sensor for the machine, requiring no explicit tachometer connection to determine transient rotor speed. The vibration and back-EMF voltage data can be transmitted to a user device, e.g., a tablet or a nearby server, and processed to estimate the speed of the rotor as it slows down from steady-state operation to standstill. The vibration data and the estimated speed are then signal-processed to generate an empirical vibrational transfer function (eVTF) [11]. This transfer function is rich in condition information for detecting and differentiating not only machinery pathologies, but also problems with vibrational mounts.

VI. DISCUSSION

Digital technology has been in use for over 20 years for measuring and metering process flows. Digital power monitoring as found in solid-state power meters has also made its way to the plug and power strip level. Many different schemes for storing or communicating information are still under exploration. Most of these solutions deploy computation hardware that is either substantially complicated in both hardware and firmware or where fully integrated custom chips and sensors are specifically developed for a particular application. Both vendors and consumers will likely find innumerable ways to mine information if made available in a useful form. However, appropriate sensing and information delivery systems remain a chief bottleneck for many applications, and metering hardware and access to metered information will likely limit the implementation of new conservation and maintenance strategies in the near future.

Sensors, actuators, and other infrastructure like power cabling that you already own can be pressed into “dual use” service. A suite of sensors has been presented in this paper that provide electronic “stethoscopes” capable of “listening” to signals of interest at relatively high bandwidth. Used creatively, these sensors permit us to think more, using signal processing and inexpensive computing to avoid installing more complex arrays of sensing hardware. Complex sensing arrays with more parts have more critical points for failure. Nonintrusive sensors minimize the addition of risks points in a control system. For example, this paper has illustrated that a highly reliable and inexpensive utility meter for tracking water consumption can be easily turned into a high-bandwidth flow meter for tracking liquid consumption. These passive mechanical meters are present in many systems and buildings, and they can become high-resolution monitoring tools at a fraction of the purchase and installation cost of a dedicated high-bandwidth flow meter. In this paper, we have also reviewed applications for power monitoring and vibration monitoring for condition-based maintenance of electric machines.

We are exploring extending the nonintrusive monitoring concept to gas mains, and to various occupancy detection schemes using air flow measurements and acoustic signals. We are also exploring nonintrusive electrical load detection by looking at both quasi-static and radiated signals associated with the operation of different loads. Thermal measurements can be incorporated in nonintrusive sensors to provide a holistic picture of critical system operation.

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