Self-adjusting Quasi-static Electric-field Sensor

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Abstract—**The US Army Research Laboratory (ARL) "Smart D-dot" sensor is a flat unattended ground sensor (UGS) that measures quasi-static ambient electric fields. The frontend transducer is composed of two conducting sheets/plates. The 31.6x31.6 cm top plate acts as the signal collector and current source, while the 36.6x36.6 cm bottom electrode provides the ground reference voltage and current sink. Electric charge is induced on the signal-collecting plate in proportion to the size of the electrode and the time-derivative of the ambient E-field. This current is input to an ARL custom printed circuit board (PCB), which contains a current-to-voltage (trans-impedance) pre-amplifier followed by analog signal-conditioning circuitry. Additionally, the gain of the pre-amplifier can be adjusted via a "smart" transducer electronic data sheet (TEDS) interface: this allows the total dynamic range to be varied an additional 73 dB on top of the measured 117 and 108 dB dynamic range at 10 Hz and 10 kHz, respectively. This paper details the testing of dynamic range and frequency response, and presents an application where the sensor monitors ambient electric fields.**

I. INTRODUCTION

Voltages on power conductors are typically measured making physical contact to the conductor with an isolated voltage probe [1] and using conventional voltage probes; for high-voltage distribution and transmission lines, potential transformers (PTs) are used [2]. This method provides a reliable way to monitor voltage magnitude and relative phase, but the equipment costs run up to $3000 per wire and installation typically requires a scheduled power outage. Standoff electrostatic sensing can be used to get the same voltage magnitude and relative phase safely at a lower hardware cost. The expense now becomes additional mathematics and more complex circuitry.

Many electrostatic sensing concepts have been proposed and demonstrated to monitor low-frequency electric fields; these include the SAIC "SEEF" and the UNCC Varactor [3] sensors. However, these sensors do not have an interface to communicate with the sensor from a computer, which presents limitations for modern "smart-energy" applications. The ARL "MD-dot sensor" [4] overcomes this lack of computer interface issue, but is designed for electric-field strengths over 10 V/m due to the small size of the sensing electrode.

II. MODELING AND DESIGN

When exposing a uniform conductor to an electrostatic field, Coulomb force moves the charges closer to or farther away from the field source, thereby causing a current; this phenomenon is called charge induction. If we assume the electric-field source is an ideal

sinusoid, then the current is proportional to the time derivative of the induced charge, and therefore proportional to the time derivative of the field. The equation for this current has been derived [5] and found to be

$$i = A_{eff}\varepsilon\omega|E|\cos(\omega t + \varphi) \tag{1}$$

If we provide a path for this current to flow to ground through analog circuitry, we can measure the charge-induced current in real time, and therefore the relative magnitude and phase of the electric-field source. A standard transimpedance amplifier will provide this path for current flow in our sensor design. The feedback resistor R_f for our transimpedance amplifier has a value of 200 kΩ, providing a 200-µV/nA gain for the first stage of signal conditioning. Additionally, a 100-Ω resistor at the transimpedance input will provide moderate protection against electrostatic discharge (ESD).

The ARL "Smart D-dot" sensor builds upon the basic D-dot sensing concept from [5]. The transimpedance amplifier is followed by a single-pole, passive low-pass filter (LPF) to produce a 20-dB/decade rolloff at the amplifier output with a 600 Hz, 3-dB point. We then introduce "smart" capabilities to the D-dot sensor by adding a microcontroller-based interface as shown in figure 1, similar to that of the ARL MD-dot sensor [4].
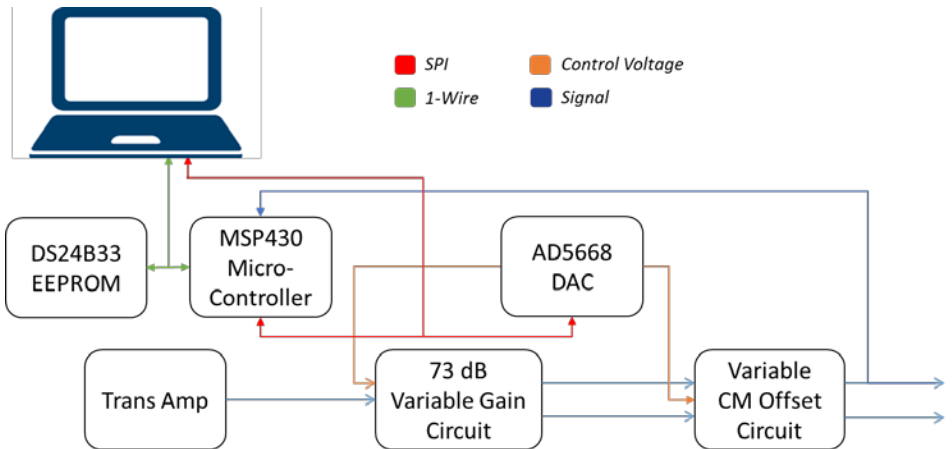

Fig. 1. The TEDS-compatible 'smart' interface allows the sensor to communicate via SPI or 1-Wire protocol to a computer or 1-Wire/SPI master device. The embedded microcontroller autonomously adjusts its own offset and gain by monitoring one of the output signals and updating the outputs on a digital-to-analog converter, as shown by the arrows in the figure.

The smart interface allows an embedded microcontroller to dynamically change the V/(V/m) sensitivity of the sensor up to an additional 73 dB to meet the desired (programmed) output characteristics. The complete Smart D-dot sensor design is shown in figure 2.

Fig. 2. ARL custom printed circuit board connected to the 0.010-m^2 top and 0.134-m^2 bottom aluminum plates, held securely by plastic screws and 3D-printed spacers (left). The completed Smart D-dot sensor with custom enclosure ensures the circuit does not contact either plate (right).

To calculate the distortion in an ambient electric field our sensor causes, represented as the effective area A_{eff} in equation (1), ANSYS Maxwell software was used to create an electrostatic model of the Smart D-dot sensor. Reasonable simplifications are made for these models: The air is modeled as free-space; all conductors and dielectrics are isotropic; and both plastic and circuit components have their geometries simplified while maintaining actual electrical characteristics. The environment around the sensor is modeled to 10 sensor dimensions. With these simplifications, the modeled solution is expected to provide better than 1% accuracy. The distortion in the field at the sensing electrode is the primary focus of this model.
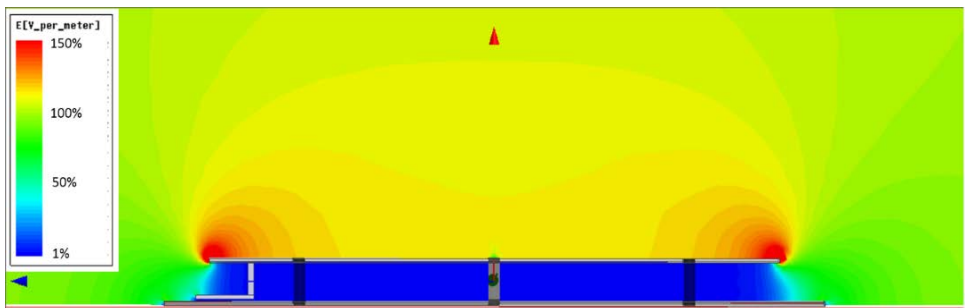

Fig. 3. A two-dimensional view showing the relative strength of a uniform, ambient, vertical electric field when the sensor is introduced to the environment. Note that 100% on the legend represents the actual magnitude of the ambient electric field.

The model used in Figure 3 can be used to estimate the electric-field "enhancement factor" that our sensor creates. This enhancement factor is the result of additional electric flux lines terminating on the top electrode, which otherwise would not flow through the electrode area. This results in an electric-field magnitude 52% greater at the surface of the

sensing electrode, and therefore, A_{eff} is larger than the physical area of the top plate. A_{eff} has an approximate value of 0.152 m²; this value is used in equation (1).

We can now derive an equation for the voltage output of our sensor as a function of the electric field. Combining equation (1) with the transimpedance gain and smart-interface gain, the equation becomes

$$V = iR_f G = (2.7 * 10^{-7})G\omega|E|\cos(\omega t + \varphi) \tag{2}$$

where G is the (V/V) gain of the smart follow-on amplifier stage immediately after the transimpedance amplifier. This stage is used to vary the sensitivity of the Smart D-dot sensor over a 73-dB range (from G = 0.031 to G = 137). For the following analyses, a nominal gain value of 13 has been assigned to G, eliminating all variables on the right side of equation (2) not dependent on the electric field.

III. CHARACTERIZATION

To accurately measure small anomalies in the electrostatic field from an energized wire, a fundamental need to characterize the performance of the Smart D-dot sensor arises. The transimpedance amplifier, 600-Hz LPF, and "smart" signal conditioning circuitry have frequency-dependent characteristics that can be quantified concurrently. We turn away from ANSYS models for this characterization due to their inability to easily and accurately model the complex circuit components, and use the ARL electric-field cage [6] for our sensor characterization as depicted in figure 4.
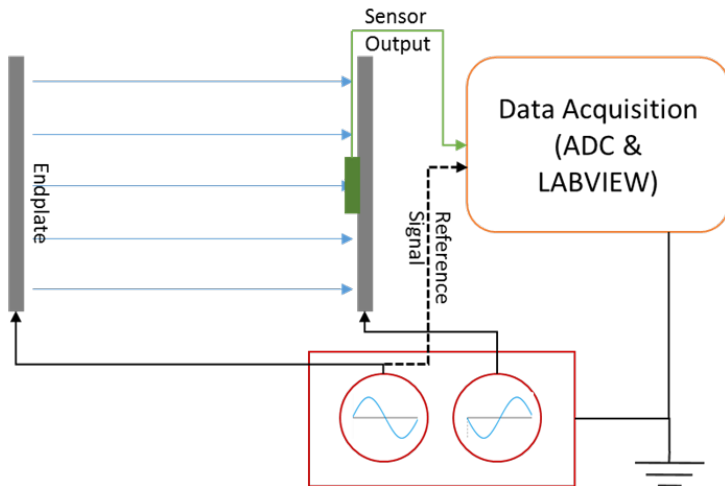

Fig. 4. The Smart D-dot sensor (green) is placed and mounted against a grounded endplate on the ARL electric-field cage. The electric-field magnitude and frequency are controlled by a function generator, while all hardware components are controlled and analyzed by LabVIEW software.

The ARL electric-field cage was modeled and measured to show <1.5% error up to 20 kHz. A custom LabVIEW program uses a phase-locked loop algorithm on 10 kiloSamples of sensor output data and an electric-field cage reference signal to extract our sensor measurements from laboratory noise. By repeating this process for M electric-field

magnitudes and N frequencies, an MxN characterization matrix can be created and analyzed. The characterization matrix is used to apply correction factors in systems which require the sensor be linear across some dynamic range or frequency bandwidth. This matrix data can also be plotted as a frequency response, as shown in figure 5.
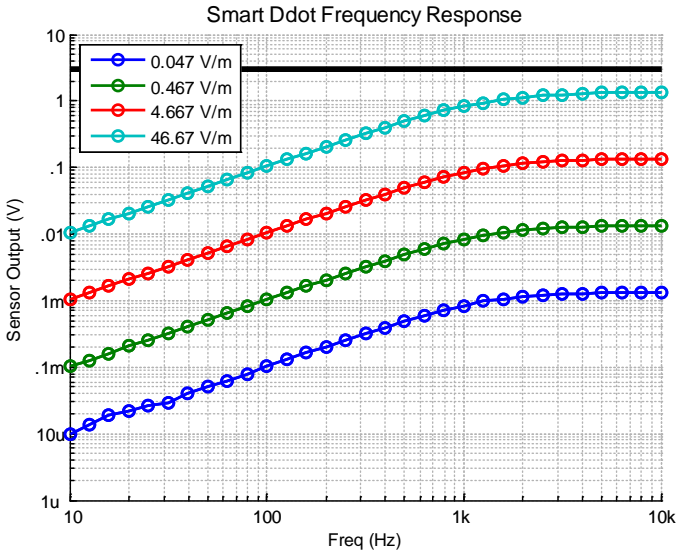

Fig. 5. The sensor response to 60 dB of electric-field strengths and 60 dB of electric-field magnitudes. This graph shows a linear dependence on frequency until its 3-dB point at 600 Hz, and the maximum sensor output denoted by the thick black line at 3.3 V.

We see the effects of laboratory noise when the sensor output is under ~200 µV on the raw Smart D-dot output, but above this value the sensor shows strong linearity across the 60-dB dynamic range we tested. The dark black line shows the sensor's maximum voltage output, suggesting the sensor has another 9–10 dB of untested dynamic range (the ARL electric-field cage setup used for this experiment was limited to 46.67 V/m for safety guidelines).

It is also important to determine the noise floor of the sensor, so we can ensure we have adequate signal-to-noise ratio (SNR) for the sensor's application. The voltage noise floor of the sensor is measured with 1 second of sampling time, then converted to an electric-field noise floor by calculating the V/(V/m) sensitivity from the frequency response in figure 4. This electric-field referred noise floor is shown in figure 6.
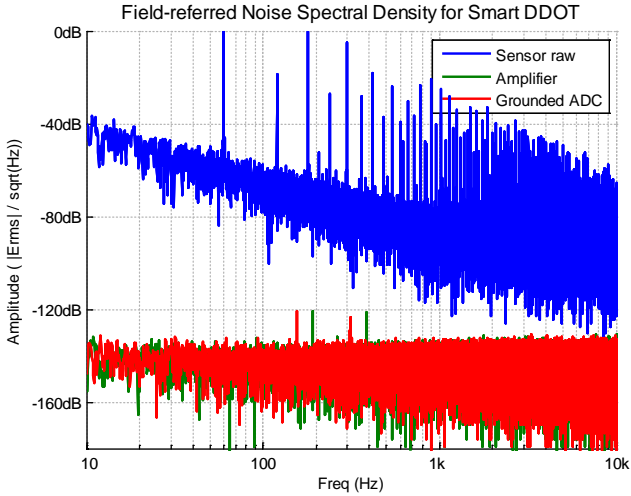
Fig. 6. The noise floor of the Smart D-dot sensor across our 60-dB testing range, compared to our open circuit (green) and grounded (red) analog-to-digital converter noise. The 60-Hz laboratory signals and their harmonics are evident, and the values have been converted to root mean square for agreement with standard noise-floor plots in literature.

While we see the strong effect from ambient AC power fields in our laboratory (60 Hz and harmonics), we can focus on non-power harmonics to better estimate the noise floor of the sensor. Combining the noise spectral density results with the raw frequency response, our dynamic range is found to be approximately 117, 118, 118, and 108 dB at 10, 100, 1000, and 10000 Hz, respectively.

IV. TESTING & RESULTS

With the sensor characterized, we can now proceed with a real-world application that suits the sensors' characteristics: measuring electric fields under power cables. The 60-Hz, 120-V_{rms} power that energizes most household electronics is typically measured by a voltage probe. So we will test and compare the Smart D-dot sensor's measurements to a standard 100/1 attenuation voltage probe with the setup pictured in figure 7.
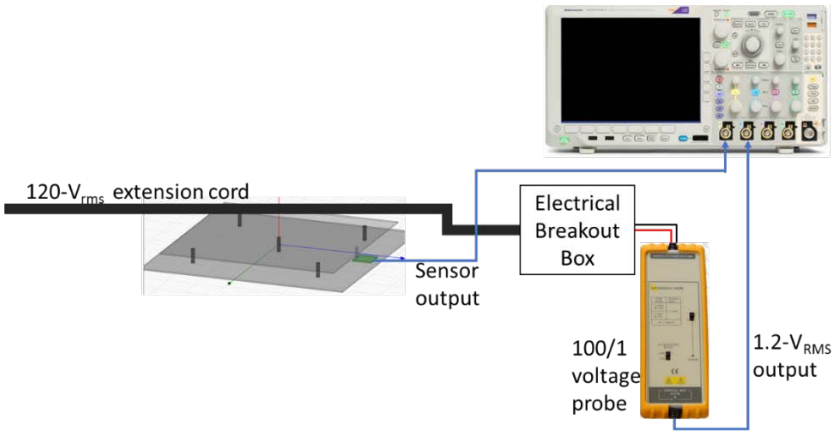
Fig. 7. Experimental setup to observe the Smart D-dot response to the electric field caused by a standard power cable's sinusoidal voltage when connected to a standard single-phase wall outlet. The cord passes over the sensor approximately 2cm above the sensing electrode.

To directly compare the voltage probe output with the sensor output, it is noted that the outputs should be 90 degrees out of phase with respect to one another, because the sensor is measuring the time-derivative of a sinusoidal electric field. We also expect to see greater effects from high-frequency content for the same reason.
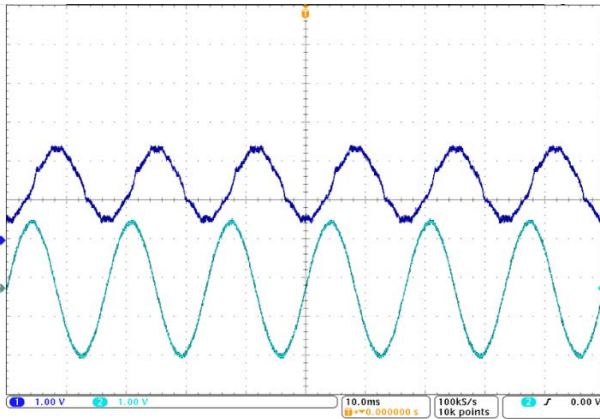

Fig. 8. Smart D-dot output (top) and voltage probe output (bottom) to a 60-Hz electric field.

Figure 8 shows our sensor is successfully monitoring the power cable's voltage at an expected 90 degrees out of phase. The sensor output also contains more high-frequency environmental noise due to greater amplification of high frequencies. Therefore, the sensor can be limited in applications with significant high-frequency noise or harmonic content.

V. CONCLUSION

A self-adjusting Smart D-dot sensor has been internally developed and analyzed. The characterization results show the device producing a consistent frequency response for

electric-field strengths and frequencies producing a sensor output over ~250 µV. A laboratory test has shown the capability to monitor voltage signals on energized cables, suggesting widespread applications with non-contact voltage monitoring.

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