U.S. DEPARTMENT OF ENERGY

Office of Electricity

Advanced Sensors Field Validation (MagSense)

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

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Project Overview

Develop and demonstrate low-cost, frequency selective current sensor (MagSense) which will allow observability of the state of health of grid components, provides detection of abnormal behavior/patterns of the grid components, as well as real-time detection of catastrophic failures.

	Fiscal Year	LTD Funds	LTD Costs	Uncosted Funds
1.4.04 Advanced Sensors Grid	2016	$312,312.00	$58,034.45	$254,277.55
	2017	$407,539.66	$259,565.21	$402,252.00
	2018	$457,037.34	$278,375.03	$580,914.31
	2019	$0.00	$162,769.55	$418,144.76
		$1,176,889.00	$758,744.24	$418,144.76

- Period of performance 4/1/2016 to 3/30/2019 (extended to 3/30/2020)
- Project lead and partners
  - Lead: Sandia National Labs, PI: Sigifredo Gonzalez
  - Partner: New Mexico State University, PI: Olga Lavrova

MagSense device is designed to eliminate these hazards

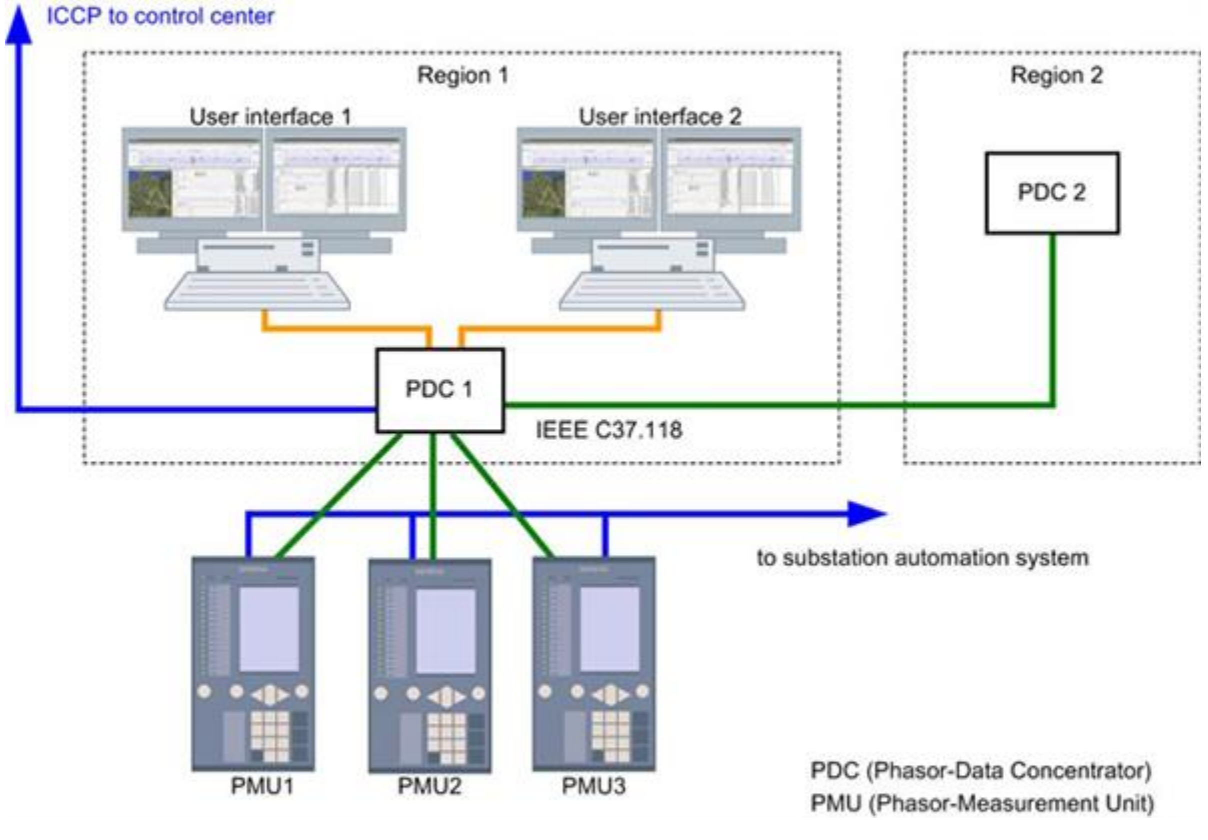
High impedance faults cause insufficient current to activate/trip typical overcurrent protection devices. Therefore fault conditions go unaddressed and pose shock and environmental concerns.

The development of this technology will provide fault mitigation and the sensitivity required for all types of faults. Complexity and cost prohibit the utilization of this type of protection but this technology . Protection coordination can be enhanced with the development of high resolution system monitoring devices.

State of the art approaches use Synchrophasor and PMU equipment

- Synchrophasor-based protection is being developed to replace electromechanical and microprocessor-based relay protection devices.
- Challenges exist[1] to this new method of detection that has the potential to respond fast enough to prevent fires and electric shock hazards caused by downed power lines. These challenges are linked to coordination of:
  - Data acquisition
  - Data storage
  - Data transmission
  - Data processing
  - Human-machine interface

A failure or malfunction in any of these results in a malfunction of the whole system.



courtesy of Siemens

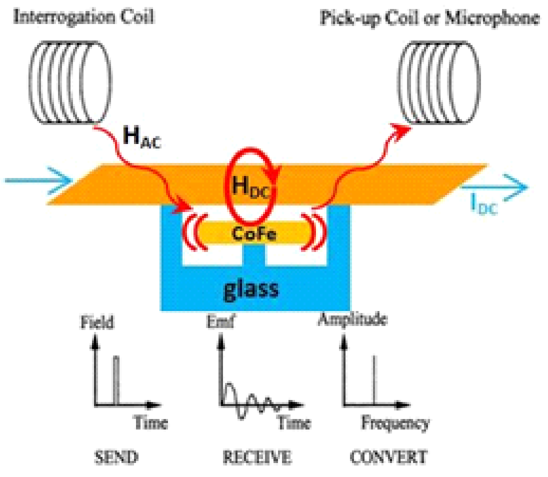
[1] Emmanuel U. Oleka, Anil Khanal, Ali R. Osareh, Gary L. Lebby, "Exploring the Challenging Issues with Synchrophasor Technology Deployments in Electric Power Grids", World Academy of Science, Enginneering and Technology International Journal of Electrical, Computer, Energetic, and Communication Engineering, Vol.9, No:9, 2015

Cyber Security concerns using Synchrophasor and PMU equipment

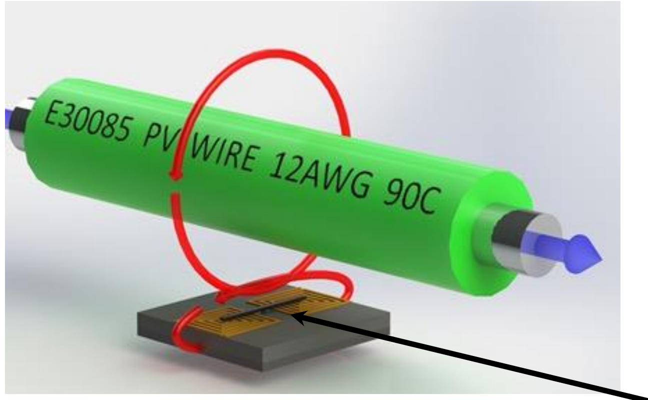
- The large amount of data requires speedy processing and communication limitations are a major challenge and advances in channel bandwidth enhancement schemes are vital to handle the explosion of PMU’s being installed on the Electric Power System (EPS).

- The high volume of communication channels will create a significant cyber security challenge and is the technologies number one challenge. Since synchrophasor systems communicate over large geographical areas and communicate with many different organizations, a high level of exposure needs to be adequately addressed.

Uniqueness of MagSense approach



We developed a low-cost, frequency selective current sensor (MagSense), which allows observability of the state of health of grid components, detection of abnormal behavior/patterns of the components, and provides real-time detection of catastrophic failures.



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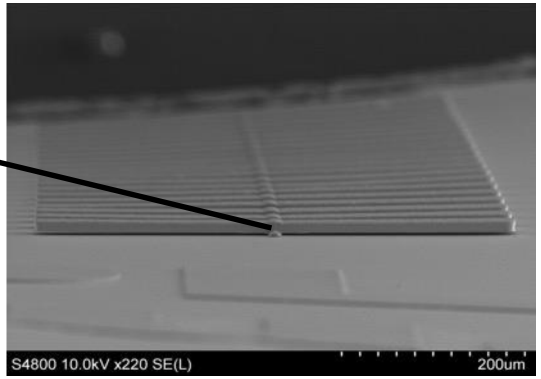
CoFe 5 MHz Resonator Array



- Single, passive sensor to detect fault currents and/or temperature excursions
    - Inexpensive (¢/module)
    - Sensitive (I_{fault} = µA) current levels
    - Fast (µs response)
-

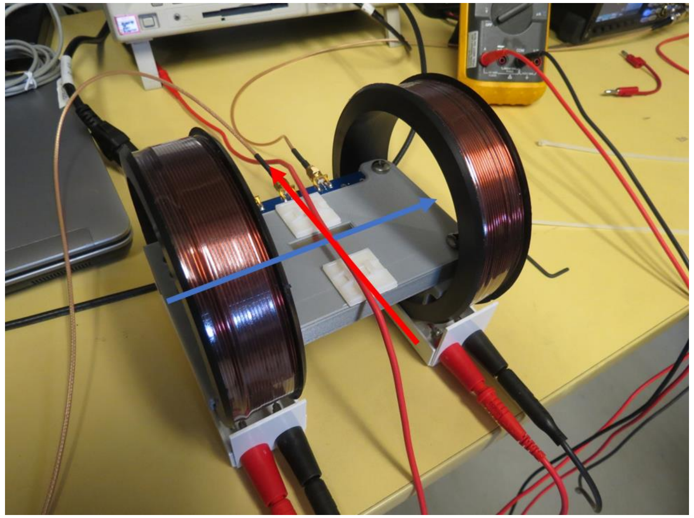
a

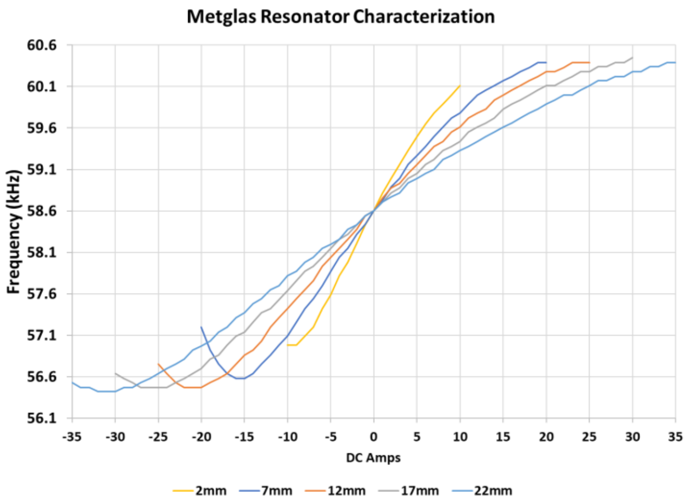
c

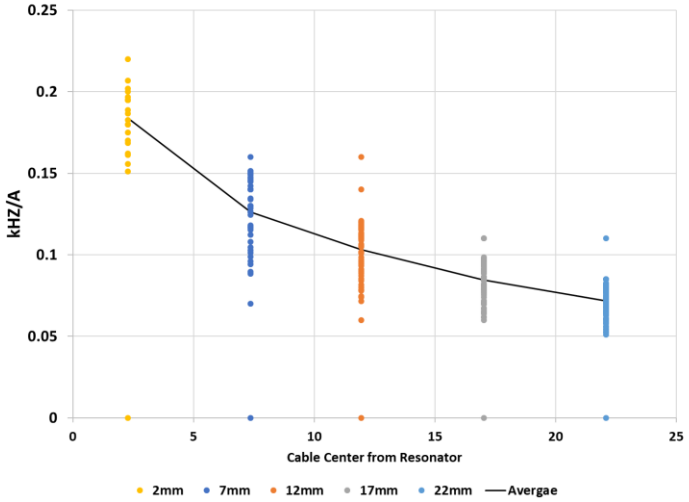
(a) and (b) illustration of Magneto-Strictive current sensing principle; (c) SEM photo of MagSense's magnetostrictive resonator

Characterization of Commercial Resonators

- Metglas resonators subjected to a DC magnetic bias to resonate at point of max sensitivity
- DC current pass through conductor and change in resonant frequency of Metglas resonator
- AC current response can be treated as "slowly" moving ±DC current response due to resonators high frequency and rapid response time







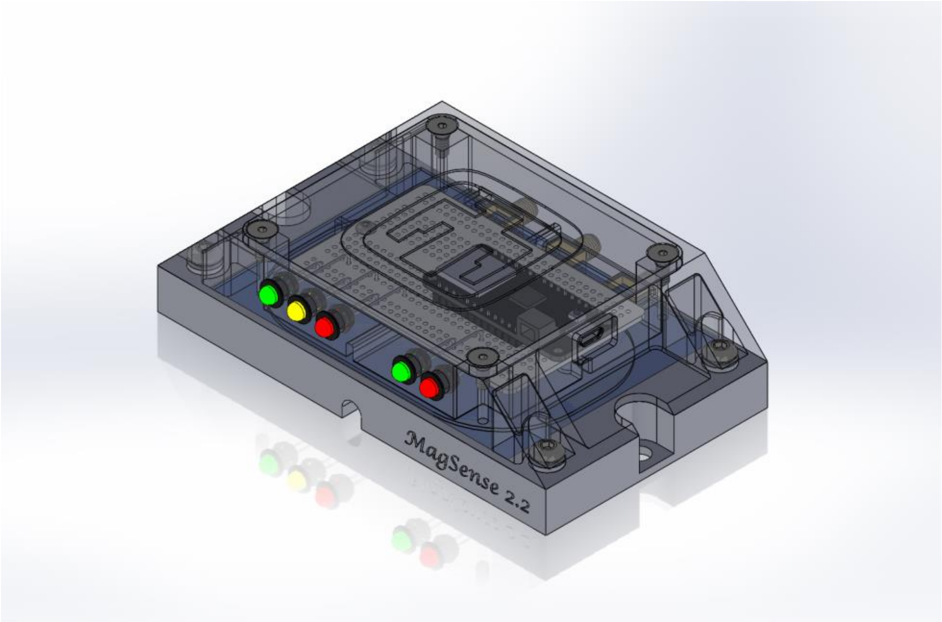
Data Collection and Processing

- Atmel M0+ microprocessor collecting data at 596000 samples per second to ensure smooth data collection over multicycle range (of resonator)
- Goertzel algorithm for DC current ranges and Fourier transform to AC current range

Two types of interrogation / information readout are possible:

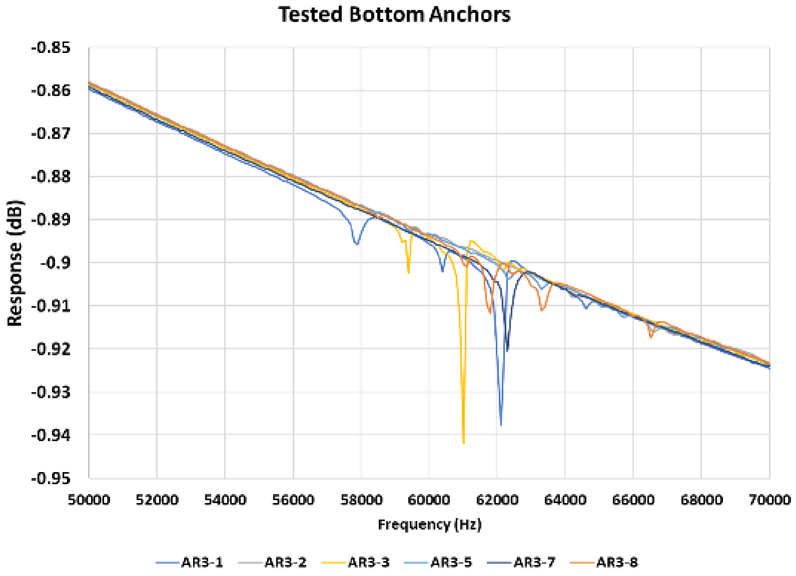
1. Passive
   - Device is interrogated manually or semi-manually
   - Lower cost option ($10 - $50 range)
2. Active
   - Device is actively "listening" and will transmit an alarm as soon an event is detected
   - Slightly more expensive option ($100 - $300 range)

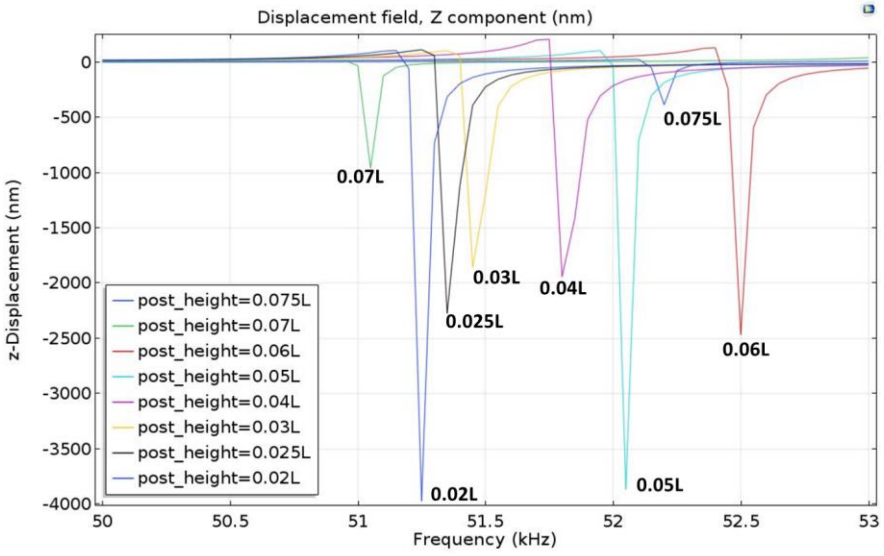
- We are working on both options, and will evaluate both of the cost/benefit trade-offs and gauge stakeholder's interest in both of the solutions.

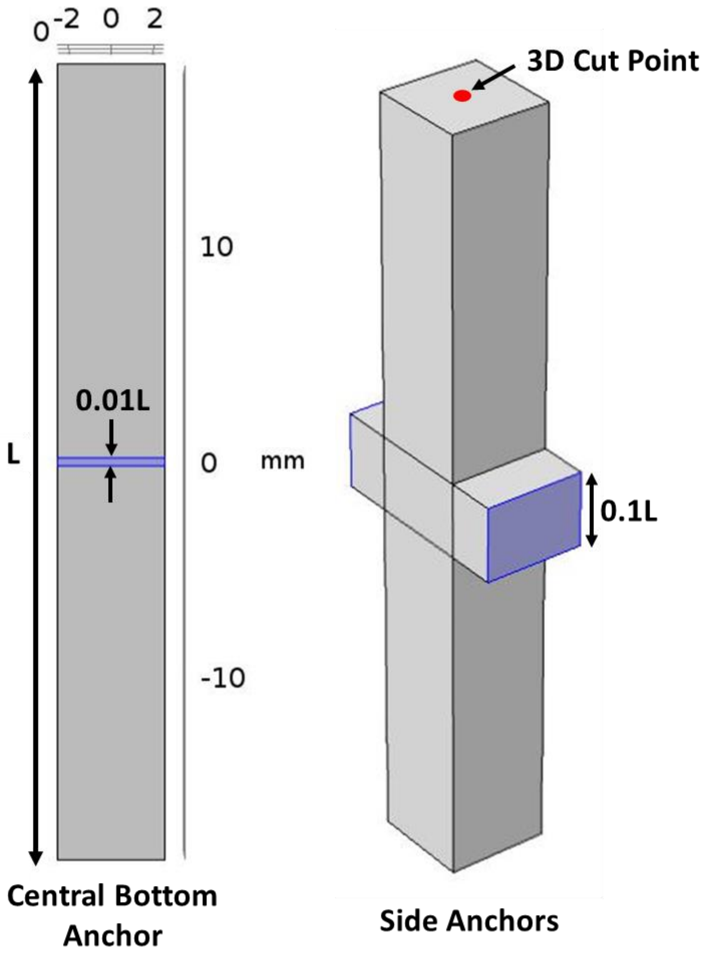


Anchored Resonators

- Anchored resonators allow for consistent response for increased measurement accuracy







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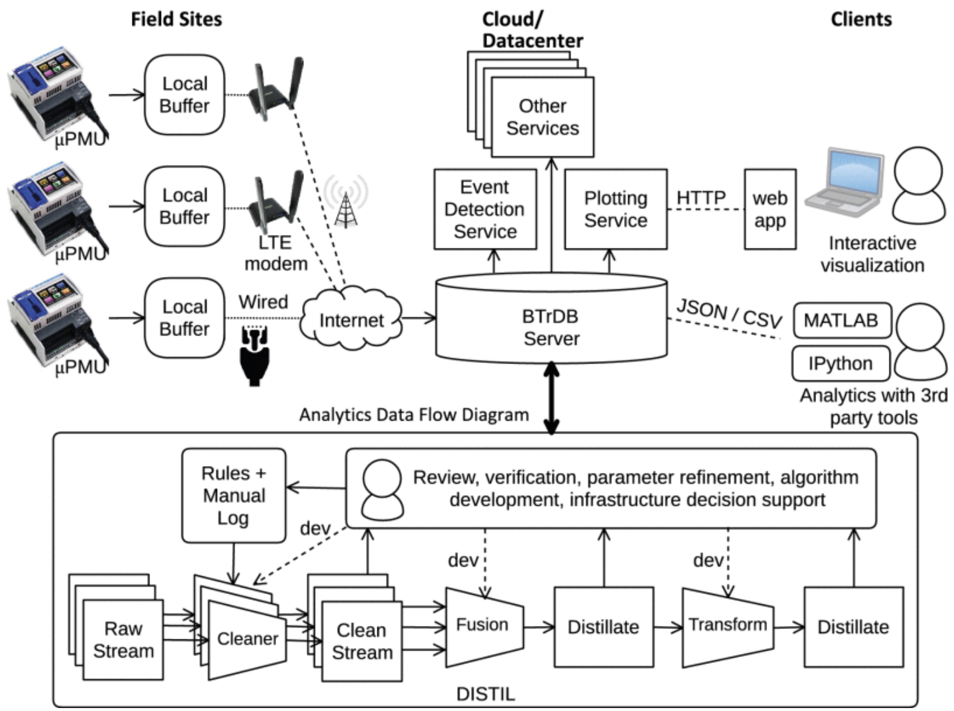
Significance of the successful MagSense implementation

- This project answers the specific need for a passive wireless sensor platform compatible for grid asset deployment.
  - Detection of AC/DC electrical faults in in critical grid assets (e.g., transformers, PV arrays)
  - Detection of difficult to detect high impedance fault conditions

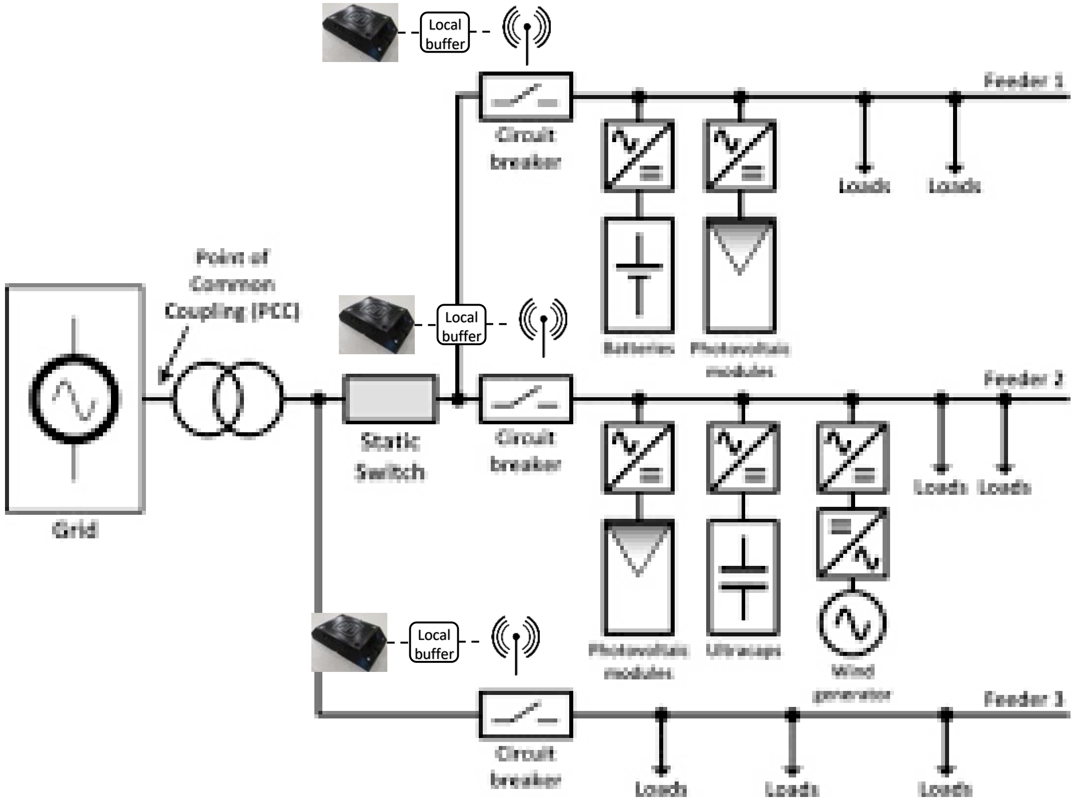
- Cybersecurity and Resiliency applications: identify critical frequencies in electric grids that can lead to failure

Significance of the successful MagSense implementation

MagSense project has the ability to provide more sensitivity and resolution to fault conditions than the some of the latest state-of-the-art technologies.



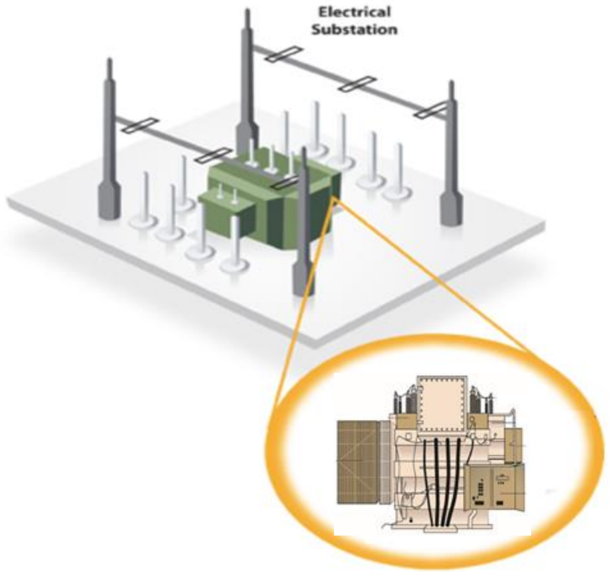
Detailed PMU system—output to grid components

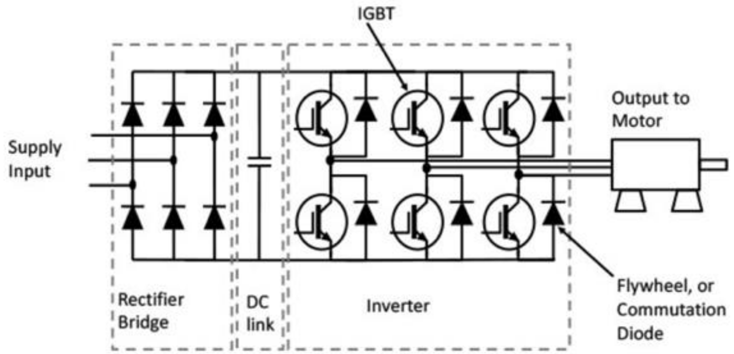


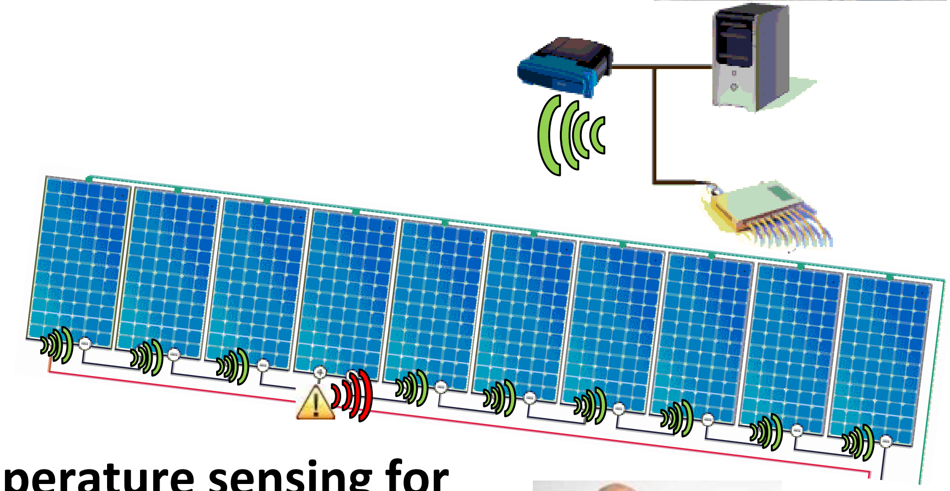
MagSense system—output to grid protection devices

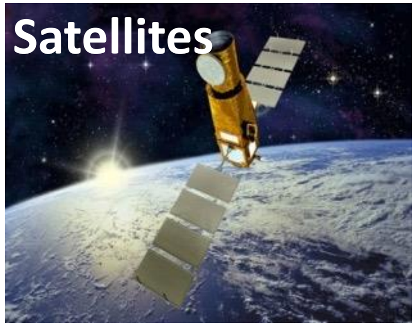
Significance of the successful MagSense implementation

- MagSense has a broad array of applications beyond of today's presentation







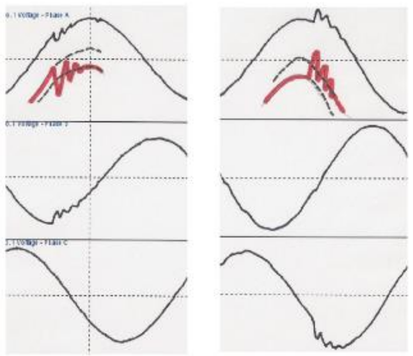


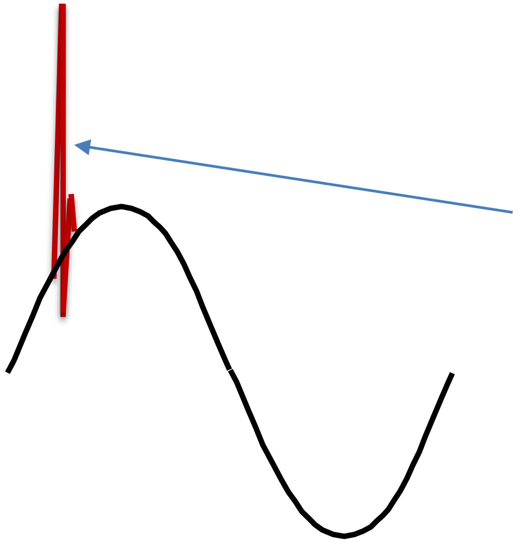
- Sensors can be wirelessly interrogated
- Data collection can be manual or automated (UAV, ground-based robotic, etc)

Temperature sensing for Electric vehicle and other batteries

Specific research questions being addressed

- Conduct a survey of high frequency events that MagSense device will be exposed and respond to during the application of the device in the transmission, distribution, and microgrid system.
- Based on survey, identify the event critical to enhance resiliency
- Demonstrate the response of MagSense contributes and meets NARM goals.





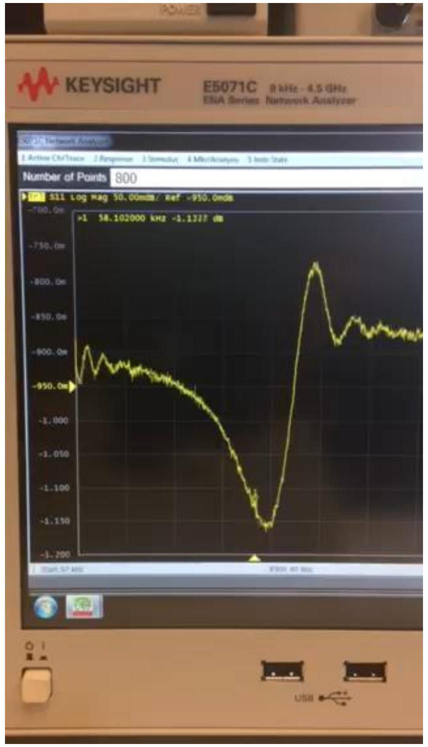
During Transient, frequency change/shift should be significantly above the steady state levels. Such difference from the steady state levels is the signal that we need to detect

Technical explanation of the proposed approach

- A -first-of-its-kind electrochemically deposited (ECD) cobalt iron (CoFe) alloy with a high degree of magnetostriction was developed by SNL;
- CoFe resonating frequency changes, depending on current (***Js***) present, and frequency change/shift can be detected:

$$f_r = \frac{1}{2L}\left[\sqrt{\frac{\rho}{E_0} + \frac{9\lambda_s^2\rho\left((|H_B + H_{DC}(t)|\cos(\beta))\right)^2}{J_s H_A^3}}\right]^{-1}$$

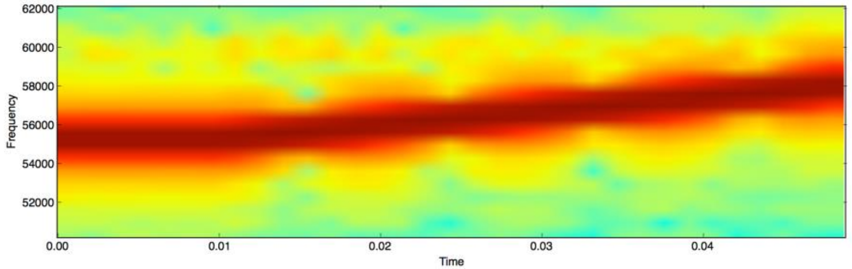
- We have fine-tuned process parameters to result in higher magnetic sensitivity parameters



- **We have demonstrated sensing of current for several important applications:**

1. Detection of DC and AC currents
   a. Application: detection of high impedance faults or ground faults in DC circuits
2. Detection of DC and AC faults
   a. Application: detection of "traditional" faults but with greater accuracy and precision
3. Detection of grid asset performance degradation or other abnormalities

Output Spectrogram:
Frequency wavelet:



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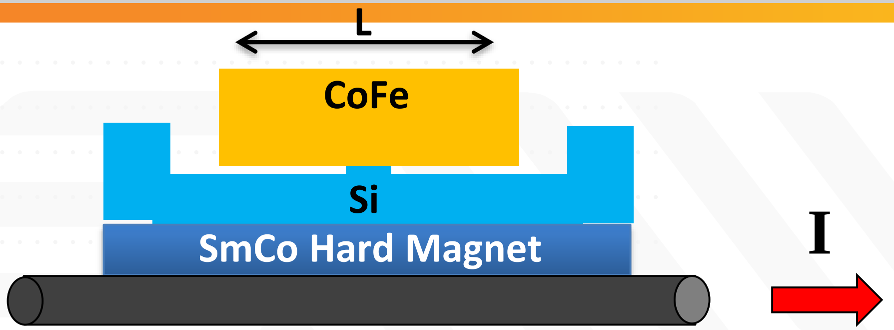
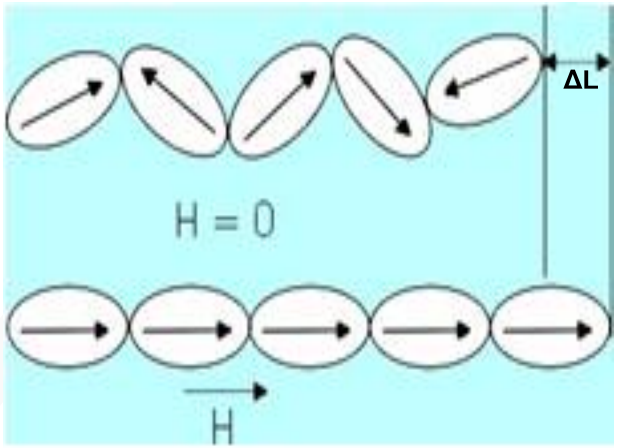
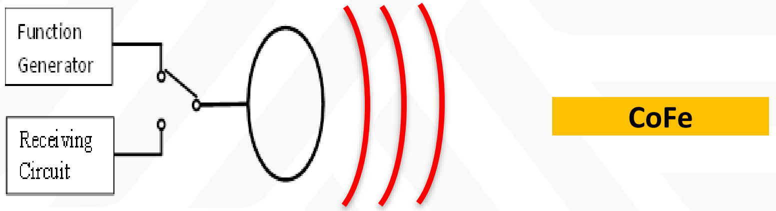
MagSense: Theory of operation



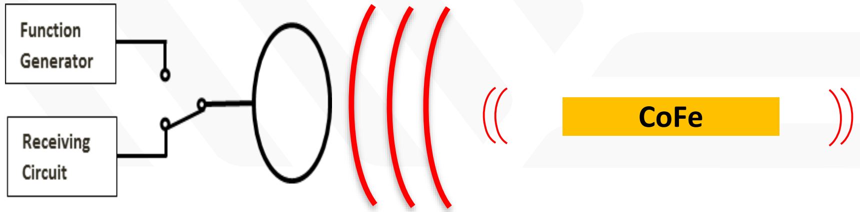
Magnetostriction, λ=ΔL/L



MagSens Cross Section



$$f_r = \frac{1}{2L}\left[\sqrt{\frac{\rho}{E_0}+\frac{9\lambda_s^2\rho\left(\left(\left|H_B+H_{DC}(t)\right|\cos(\beta)\right)\right)^2}{J_s H_A^3}}\right]^{-1}$$



Project schedule, deliverables, and current status

FY 2019

1. Work with a selected utility to install MagSense on an actual feeder and complete field testing over a variety of current conditions expected in the utility distribution systems.
2. Develop remote communication (via TCP/IP) capability for communication between utility's central office and MagSense
3. Create self-contained system capable of remote communication of saved data (magsense + Arduino via wireless)

Additional FY 2019 Resources = $250K (demonstration purposes)

Milestones:

~~March~~ August 2019: Finalization of selection of utility host site for MagSense –El Paso Electric (Tortuga substation)

~~May~~ September 2019: Finalize test plan with the utility host site—collaboration with New Mexico State University

~~August~~ October 2019: Utility testing of prototype MagSense at utility host site

~~September~~ February 2019: Report completed outlining results of testing.

24kV Substation on NMSU campus

Anticipated challenges and risk mitigation strategies

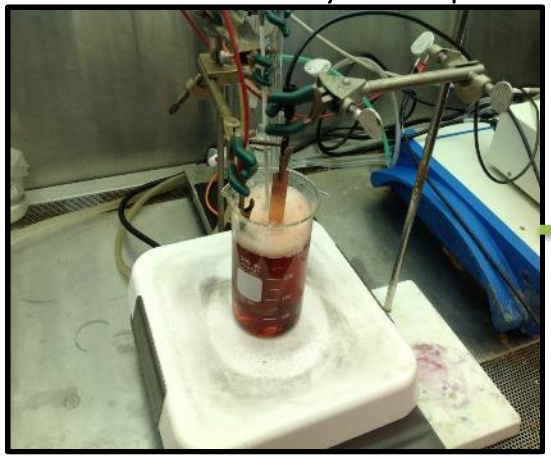
- Use of present Arduino microprocessor allows for fast sampling and calculations but limits to one process at a time (i.e. cannot collect data while determining frequency range)
  - Development of FPGA (field programable gate array) program needed to achieve continuous data sampling while post-processing

- Resonator anchoring tends to dampen response signal
  - Need to improve fabrication process and select resonator design to limit dampening of the resonator response

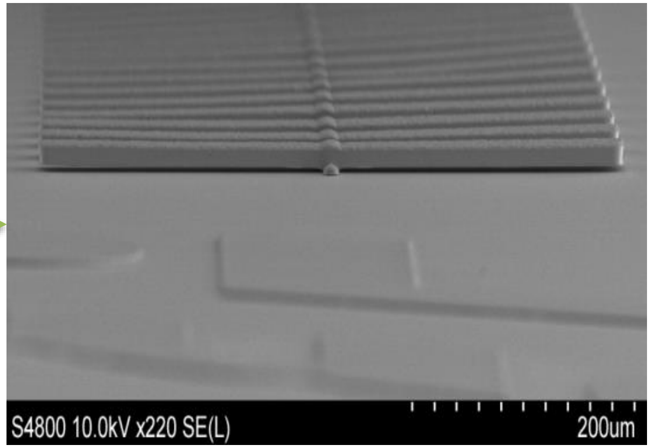
MagSens: CoFe Alloy Development

Electrodeposition of CoFe:

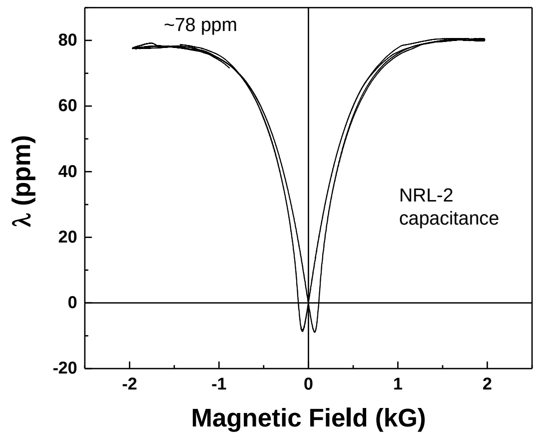
Beaker scale chemistry development



Microfabricated CoFe resonator array



Magnetostriction measured at NRL of as-deposited films



Problems: CoFe films work well for DC applications but do not respond to frequency

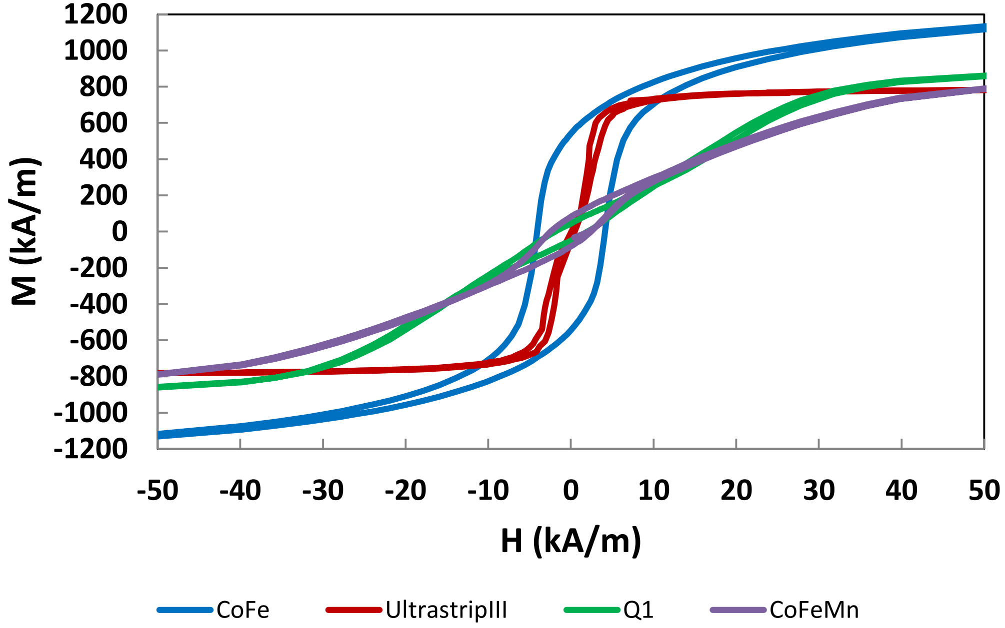
- Possible causation examined:
    - High conductivity leads to Eddy current loss (internal loop currents that oppose the time-varying magnetic field)
        - Resistivity (ρ) of our CoFe alloy is 0.2 μΩ-m compared to 2.3 μΩ-m for commercial METGLAS® alloy
        - Power loss per cycle scales as ρ^{-1}, could reduce the signal amplitude by a factor of 10
    - Hysteresis loss
        - Switching energy loss equal to hysteresis loop area
    - Piezomagnetic coefficient may be low, $d = \delta\lambda / \delta H$
        - Determines degree of resonator amplitude as a function of applied AC magnetic field
    - Squareness ratio, $S = M_r / M_s$
        - High S ratio: not much change in magnetic flux, Φ, from a low amplitude AC magnetic field

MagSens: CoFe Alloy Development

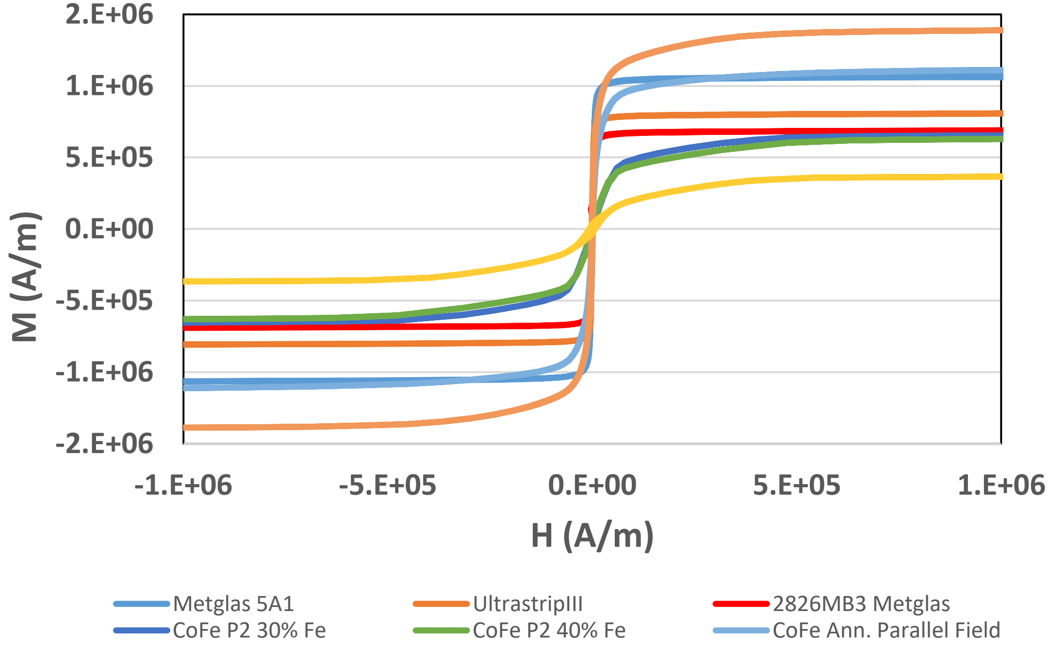
To overcome problems with frequency response:

- **Increase electrical resistivity by addition of P and B**
- **Adding additional elements such as Ge, Mo, Cr, and Mn to magnetically soften the resonators**
- **Result is a large range of control over CoFe alloy magnetic properties**

Control of coercivity across a range of H_c



Variability of M_{sat}, M_R, squareness and permeability through annealing and stoichiometric changes



Next steps

- Demonstrate specialization of sensors for different events detection
  - Voltage/current droops/surges
  - Equipment harmonics due to degradations
  - Power/energy theft
  - Other, etc
- Environmental reliability/sensitivity of MagSense
  - Incorporate permanent bias magnet (low power option) to resonator.
  - Build more advanced electronics for higher frequency signal detection.
- Finesse communication/reporting designs – based on stakeholder feedback
- Work with data integration and machine learning to:
  - Incorporate events/abnormalities detection into analytical methods for better visualization and controls
  - Analyze local data storage vs data transmission options for ML
  - Integrate with other applications (power electronics, other transmission and distribution infrastructure)
  - Integrate other peripheral sensors (thermocouple) for added information
  - Combine uPMU and communication infrastructure to realize better cost points

Broader Impact

- When commercialized, this sensor will drastically reduce the costs associated with sensors manufacturing and deployment, as well as enable fundamentally more precise sensing and detection of faults and abnormalities
- **Two patent applications**:
  - US Appl 14/876,652 “Electrodeposition processes for magnetostrictive resonators”.
  - Disclosure: “Passive Magnetoelastic Smart Sensors For A Resilient Energy Infrastructure”
- **Presentations:**
  - “Optimized Co-Fe-B and Co-Fe-P Alloy Films for Electroformed Resonators” Jamin Pillars, Eric Langlois, Christian Arrington, Isaac Dyer, Patrick Finnegan, Christopher St. John, Todd Monson, presented at Electrochemical Society conference, 10/7/16
  - “Cobalt-Iron-Manganese Electrodeposition for High Performance Magnetoelastic Resonators”, J. R. Pillars, E. D. Langlois, C. L. Arrington, and T. C. Monson, presented at Electrochemical Society conference, 10/4/18

Contact Information

Thanks for the opportunity

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