Harvesting Energy from Energized Conductors

Igor Paprotny

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Outline

- Introduction/Motivation
- Overview of AC Energy Scavenging
- Our AC Scavengers
  - Mesoscale Design (PZT bimorph)
  - MEMS Design (AlN quad-folded spring)
- Conclusions/Future work
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The U.S. Power Grid

- Contains:
  - 9,200 generating units
  - 1,000,000 MW capacity
  - 300,000 miles of T. lines

Department of Energy

Congressional Budget Office

DeviceDaily.com
There are Challenges

- Increasing number of outages:
  - A 126% increase in non-disaster related blackouts affecting at least 50,000 customers
    - 36 in 2006 alone!
  - U.S. electricity blackouts skyrocketing, CNN, Aug. 9, 2010

- Reduced Transmission $$'s$$
  - $5\,B in 1975
  - $2.5\,B in 2000

- Renewable Energy Penetration

The New “Smarter” Grid

- Smart Grid → dramatic increase in number of sensing nodes on the grid
  - Staggering numbers: PG&E alone estimate the need for 900,000 I/V sensors on their network
  - Prohibitive sensor fabrication ($3,000 pr. node) and installation costs
The New “Smarter” Grid

Smart Grid → great opportunity for MEMS

MEMS Power Systems Sensing

- Using MEMS technologies, we can:
  - Dramatically reduce the cost of sensors for power systems
    - Batch processing
    - Wafer-level integration
  - Reduce installation cost/nuisance
    - Small, easy to install sensors
    - Can be embedded in new, or attached to legacy equipment
  - Self-powered
    - Low-power MEMS sensors and radios

MEMS is Smart Grid enabling!
Our Goal

Ubiquitous sensing in power systems

- Appliances extension cords that report power usage
- Wireless “sticky tab” current and voltage sensors
- Underground cables that report status of their operation
- Sensor to measure powerflow in the Smart Grid

Will improve:
- Energy efficiency
- Utilization and operation of our power grid
MEMS Proximity Sensors

- Advantages:
  - Small and inexpensive
  - Easy to fabricate and encapsulate
  - No galvanic contacts necessary
  - Low or no power

Diagnostic Sensors
Prognostic Health Management (PHM)

Underground Power Distribution Cable

Paprotny et al., ISEI 2010, Seidel et al., ISEI 2010
Ongoing Implementation: Sub-metering

- Implementing the modules to sub-meter selected circuit-breaker panels in Cory Hall, UC Berkeley
- Modules are “sticky tabs” placed on top of the circuit breaker

AC Energy Scavenging

- Scavenge magnetic energy generated by a current in a nearby conductor
- No galvanic coupling with the conductor
- Couple to the AC-generated magnetic field
AC Energy Scavengin Overview

- **Current Transformer (CT)**
  - Large P.
  - No OCP
  - No zip-cords
- **Piezoelectric AC Scavenger**
  - Moderate P.
  - No encircle
  - Zip-cords
  - OCP
  - Moving parts
- **Coil w. flux concentrators**
  - No encircle
  - No OCP
  - No moving p.
  - Low voltage
- **Rogowski Coil**
  - No OCP
  - Instaion
  - Low Power

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Piezoelectric AC Energy Scavenger

\[ F = B_{r-y} \int \frac{d(H_y)}{dy} dV \]

\[ I(AC) \]

Electrical \rightarrow Mechanical \rightarrow Electrical
Piezoelectric AC Energy Scavenger

(4) overcurrent protection  (3) storage

(2) power conditioning  

(1) transducer

System Components

Investigating Two Approaches

Mesoscale

- Cantilever w. magnet
- Maximize power

MEMS

- Maximize power within strict size constraint
  - IC-sized unit
Mesoscale AC Scavenger

- PZT bimorph
- Dual magnet configuration
  - Designed to couple to a single conductor
- Overcurrent protection

Experimental Results

Demonstrated harvesting of 11 mW from 50 A_{RMS}
MEMS Design

- Fit within $10 \times 10 \times 4$ mm$^3$
- Magnetic coupling optimized for zip-cord
- Based on AlN, Silicon

MEMS Design

- Quad. fixed-fixed spring system*
- Electrode patterned to avoid charge cancelation
  - Optimized

*Inspired among other by A.C. Waterbury et al., IMECE 2008
Modeling

- At present, designed for low current operation (1-2 A\textsubscript{RMS})
  - Requires overcurrent protection
- Modeling:
  - With single AlN layer, 2 µW
  - Multiple layers/design modifications \rightarrow 10s µW

Fabrication Process

- SOI process
  - Using conventional NdFeB magnets (K&J Magnetics, Inc.)
- Fabrication ongoing!
Conclusion

- Developing AC energy scavengers to support self-powered power systems sensing
- Coupling to the AC magnetic field using a magnet gives us an advantage over other “coil-based” methods
- Mesoscale AC Scavenger:
  - We have demonstrated scavenging 11 mW from 50 $A_{\text{RMS}}$
  - Working on overcurrent protection
- MEMS AC Scavenger:
  - Should be able to scavenge 10s of µW
  - Fabrication ongoing

Next Steps – Challenges

- Overcurrent protection
  - How to efficiently dissipate energy during overcurrent conditions
    - Steady-state overcurrent
    - Fault current (e.g., lightning strike)
- Size-limitations of MEMS AC Scavenger
  - How small can MEMS AC Scavenger be to still generate energy
    - Efficient (MEMS) power conditioning
    - Theoretical limits?
    - Store mechanical energy?
Next Steps – Challenges

- Resonant Frequency Modification
  - How to change the resonant frequency of the scavenger to match/miss-match the driving frequency
    - Nonlinear springs/material

- Benign Sensor Placement
  - Prove to the power companies that my sensor does not degrade equipment performance.
    - Interesting physics

- Longevity Engineering
  - Will my sensor/scavenger work for 40+ years?

- MEMS/Wafer level integration

Questions?

http://www.eecs.berkeley.edu/~igorpapa/
igorpapa@eecs.berkeley.edu
Radio Mote

- Wireless reporting
  - Enable
    - hermetic packaging
    - Large-scale deployment

- Low-powered radio motes
  - TI eZ430-F2013
  - Dust networks
  - Pico cube

- IEEE 802.15.4 protocol
  - Secure
  - Sensor → mesh network → www