Imperial College London

Energy Harvester Powered Sensors: A Holistic Approach

Paul Mitcheson *et al*

EH Network 2013 meeting

holistic energy harvesting

Imperial College London

holistic energy harvesting

Outline

Overview of a recently completed EPSRC project:

Next Generation Energy-Harvesting Electronics: A Holistic Approach

Four main areas, highlights of each:

- Adaptive Harvesters
- Power Electronics

} *Closely related*

- Energy Modulated Computation
- Modelling

DIODES INCORPORATED

ARM

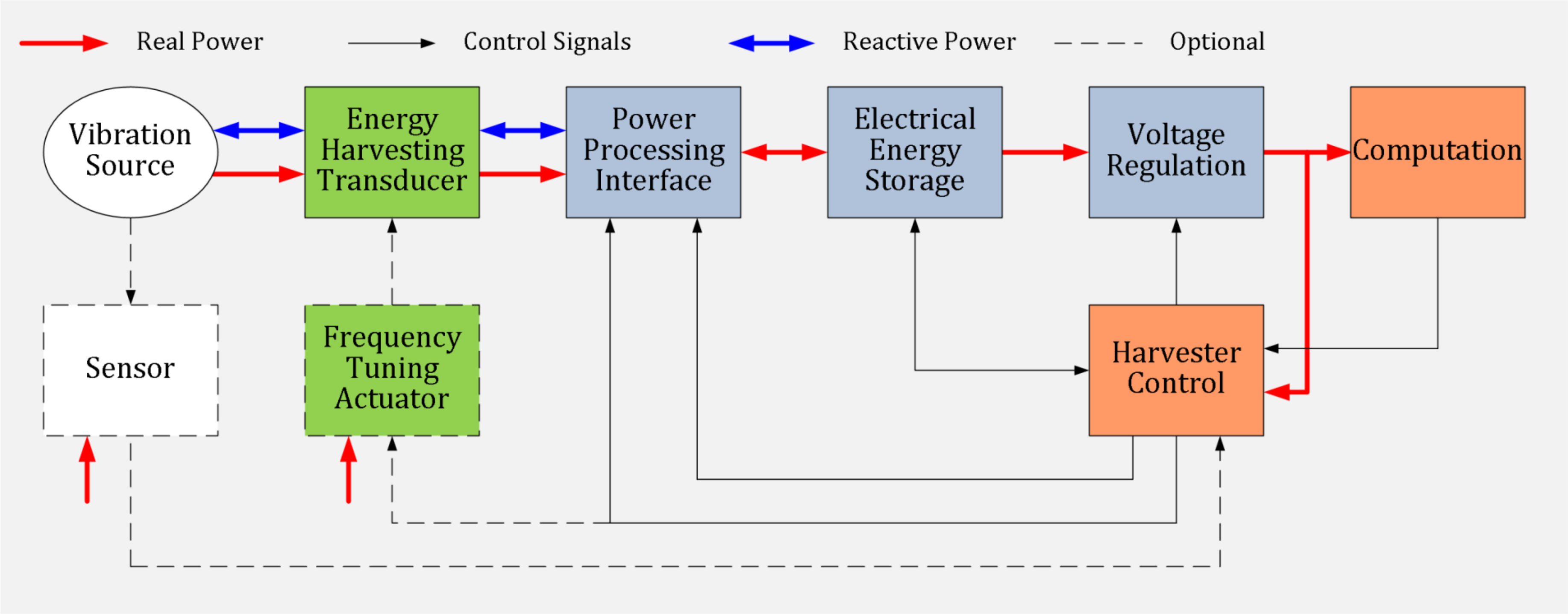
Mentor Graphics

dialog SEMICONDUCTOR

Imperial College London

holistic energy harvesting

The System



Theme A has run throughout the project and involves Imperial, Bristol and Southampton

Imperial College London

holistic energy harvesting

Adaptive Harvesters and Power Electronics

Adaptive Harvester

Two degrees of freedom in a motion driven harvester:

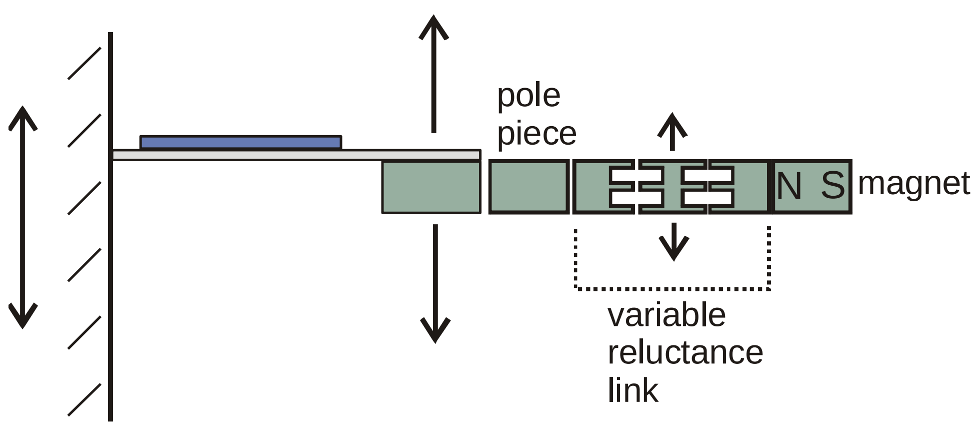
- Tuning Frequency
  - Investigated here with variable reluctance to create a magnetic potential well (in contrast to broadband techniques)

- Tuning Electrical Damping
  - Investigated using MPPT control of a boost rectifier and with piezoelectric harvesters and single-supply pre-biasing

Tuning both of these is important in many real world applications – where excitation frequency and amplitude change

Basic Concept – Magnetic Potential Well

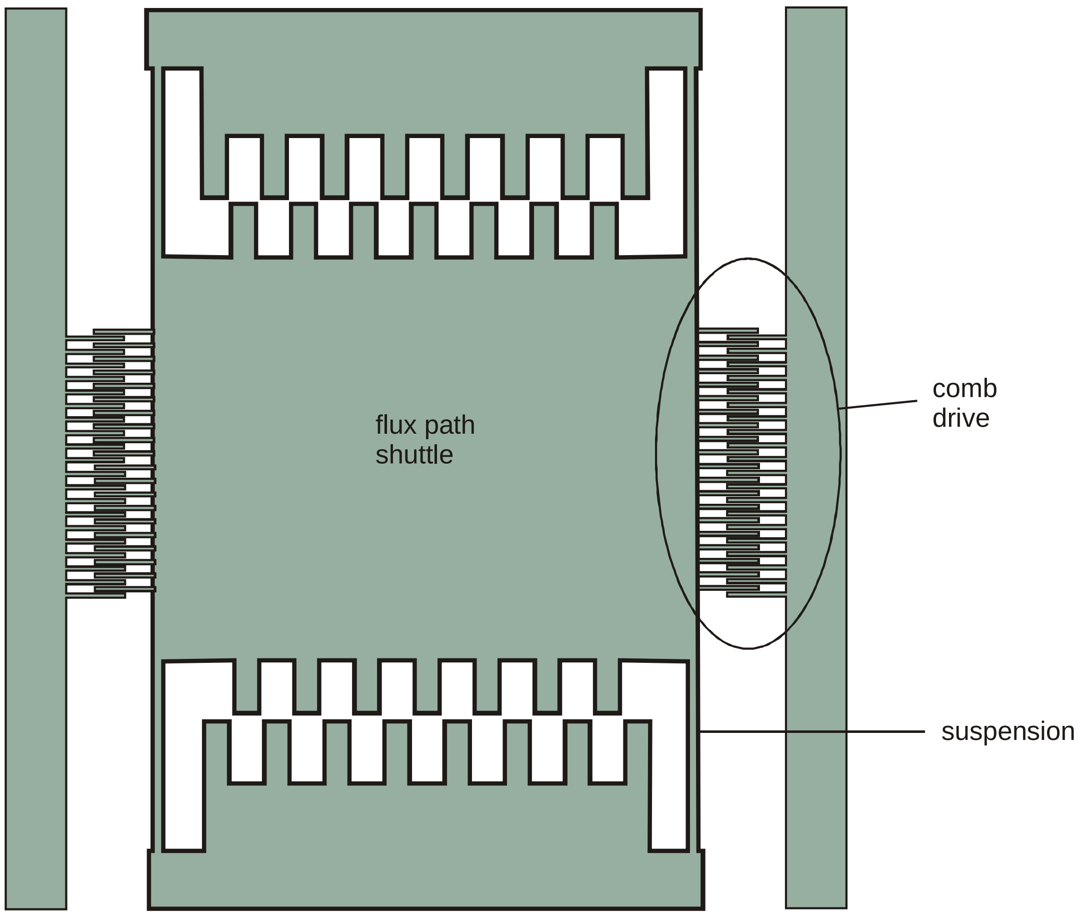
- Variable reluctance link
- Use permanent magnet, linked to oscillating proof mass by low reluctance path to pole piece
- Vary reluctance of this path by introducing a variable air gap
- Control this gap by MEMS electrostatic actuator
- This arrangement means the MEMS structure doesn't need a permanent magnet on the moving part – making fabrication and assembly easier



Imperial College London

holistic energy harvesting

MEMS VRD



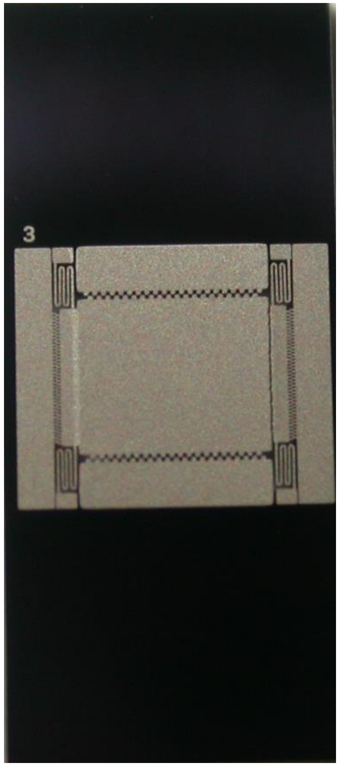
- Electrostatically actuated
- Alter magnetic reluctance between each end of the VRD

Imperial College London

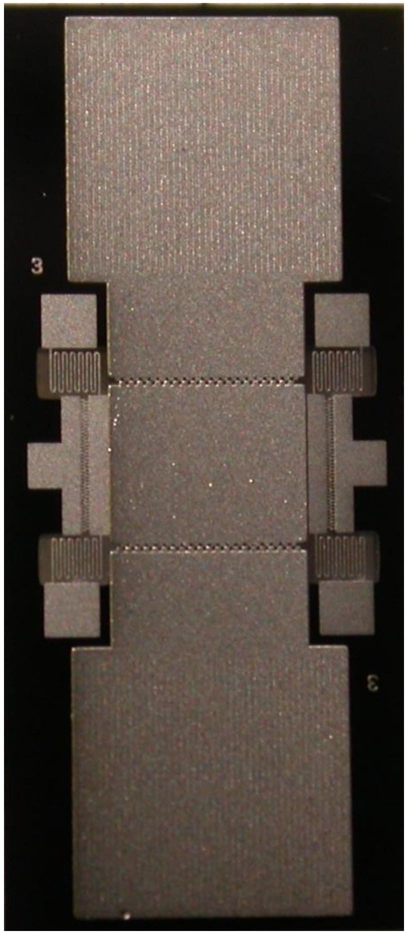
holistic energy harvesting

Picture of Fabricated MEMS VRD

Die size comparison

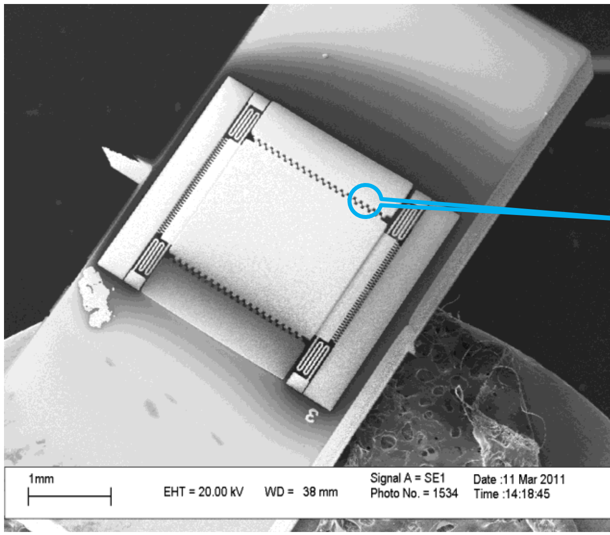


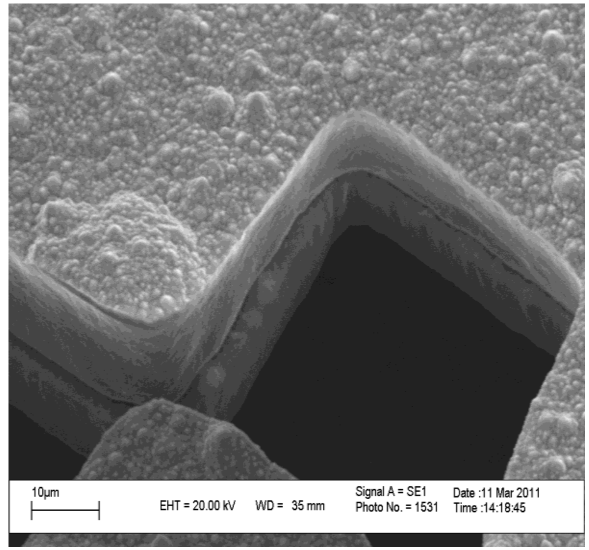
Previous fabricated die

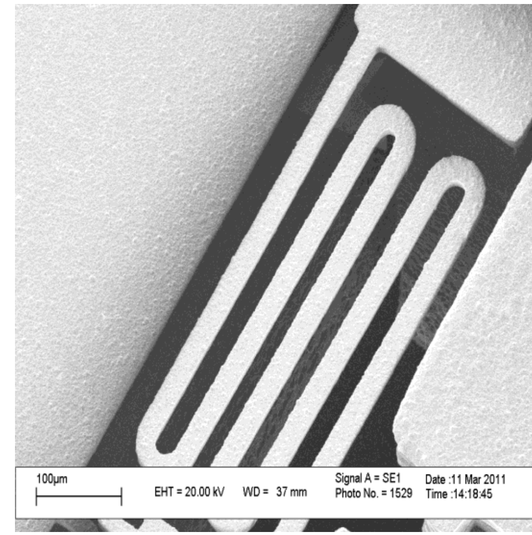


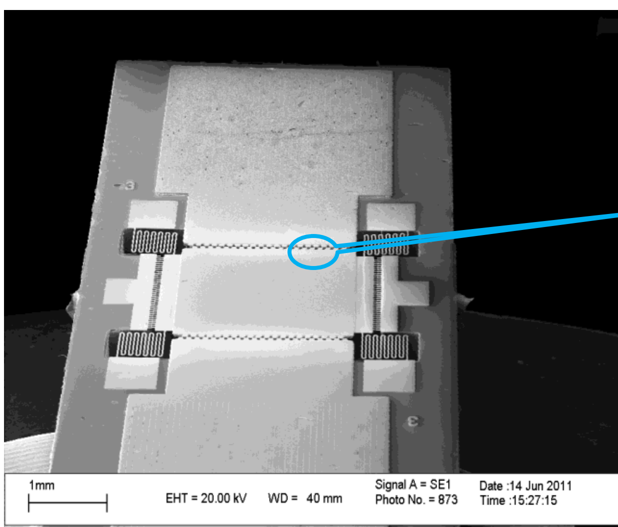
Recent Fabricated Die

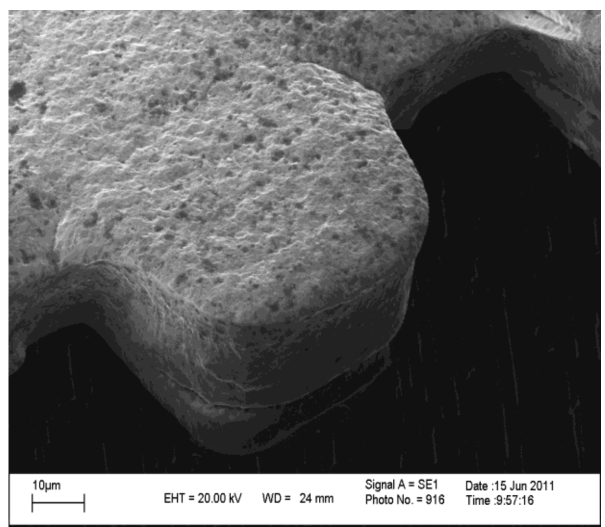
SEM Picture of the fabricated device

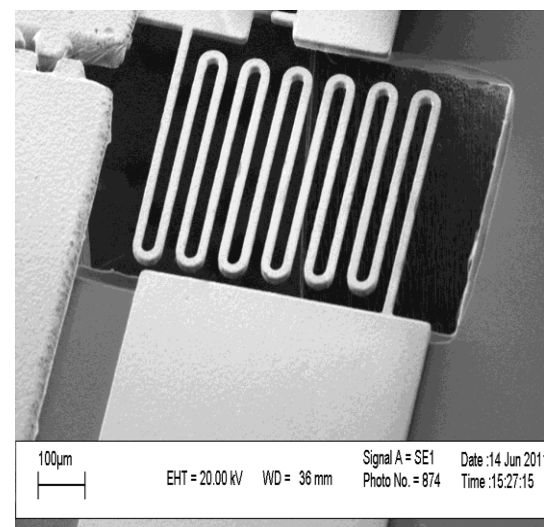








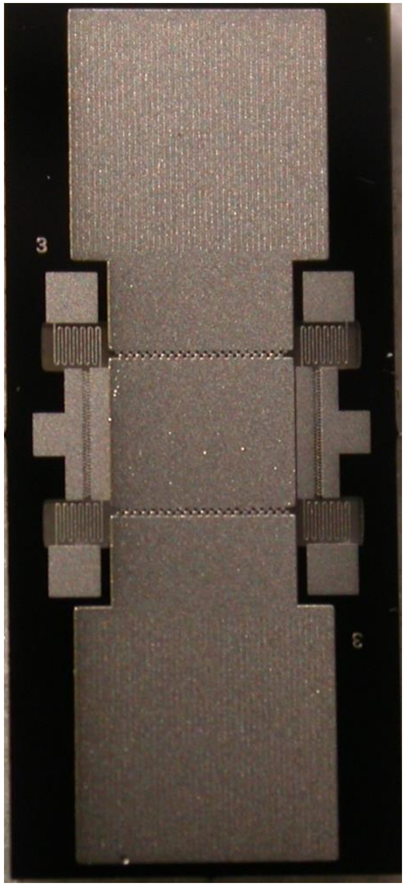




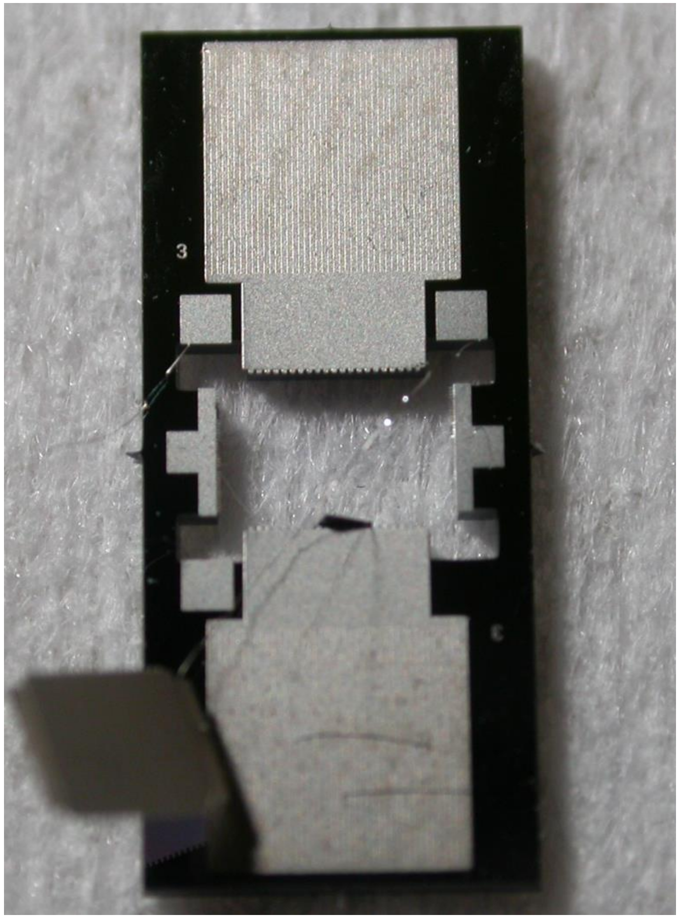
Imperial College London

holistic energy harvesting

VRD Difficulties - Manual Placement of Magnet



Before placing magnet on VRD



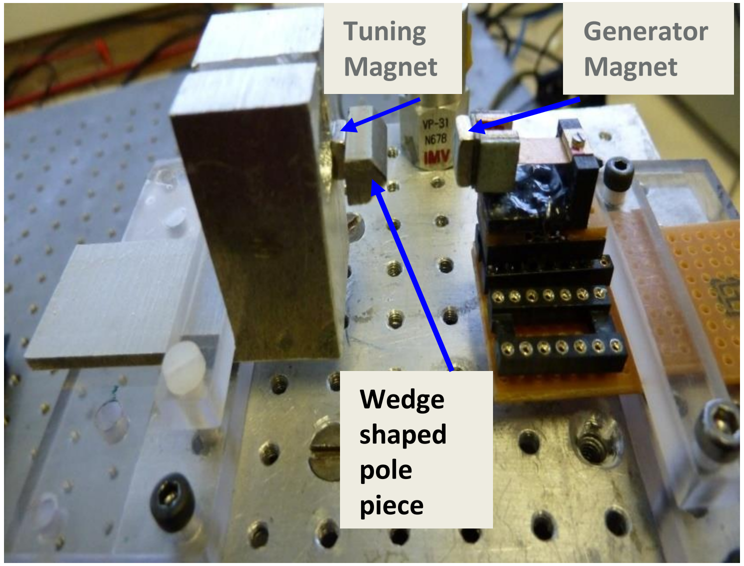
Movable part of VRD has pulled off due to magnetic force and broken the die

Macroscale Prototype

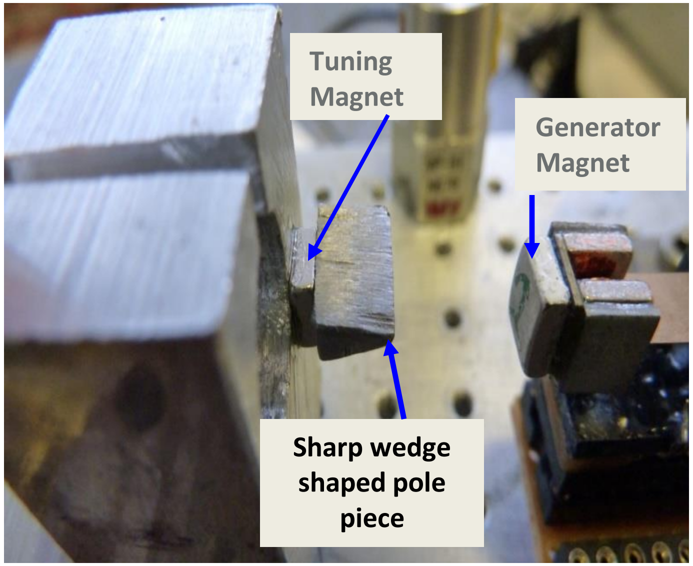
- The MEMS VRD was unable to generate sufficient changes in force to show a good tuning range.
- In order to demonstrate the effect of a magnetic potential well on tuning, a macro scale prototype was created
- Significantly less force can be achieved to perform tuning by creating a magnetic potential well, rather than simply straining a cantilever
- Various experiments were conducted to measure the force required to tune, using shaped pole pieces

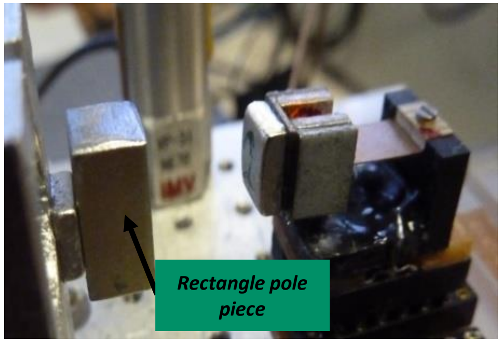
Magnetic tuning: Effect of field shape

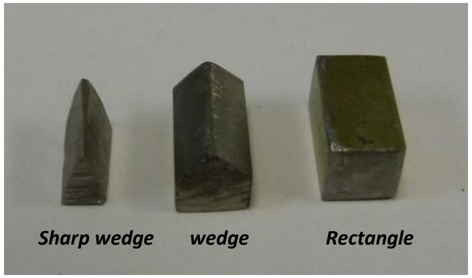
Test arrangement with sharp wedge shape pole piece



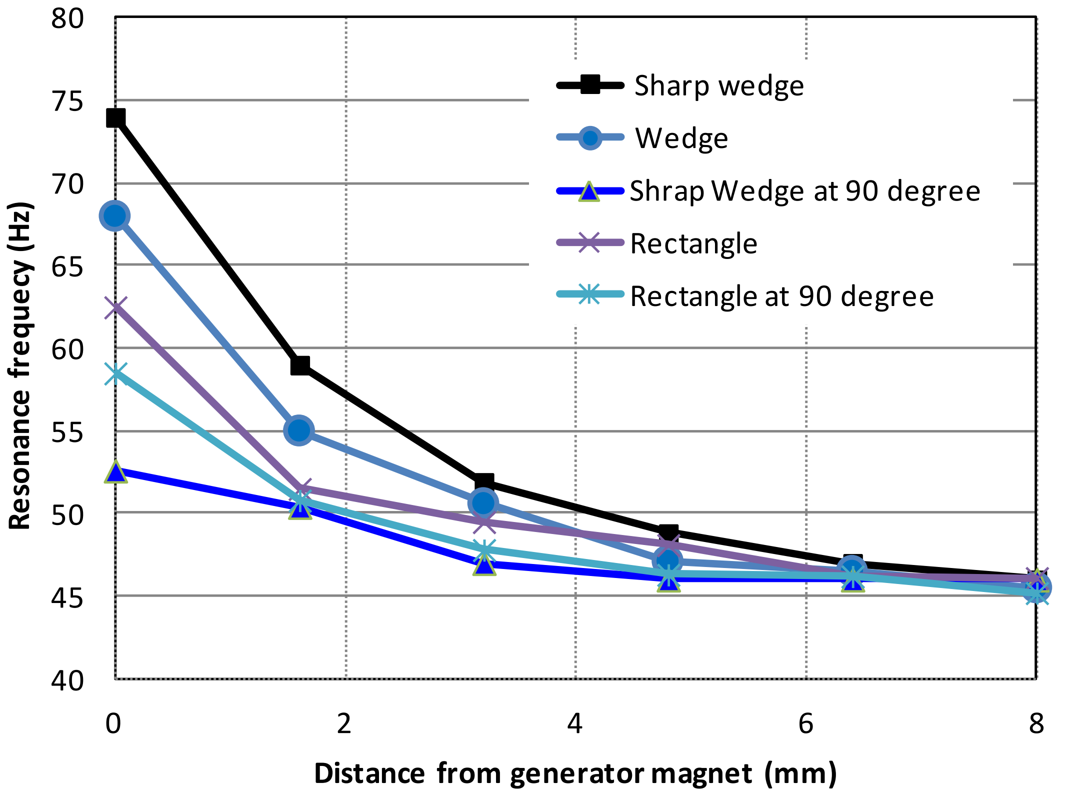
Test arrangement with wedge shape pole piece





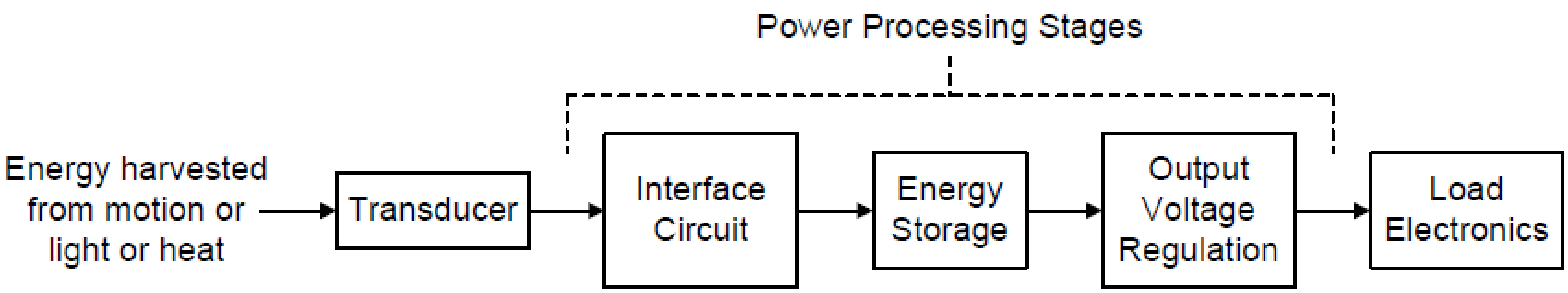


Shaped Pole Piece Tuning Results



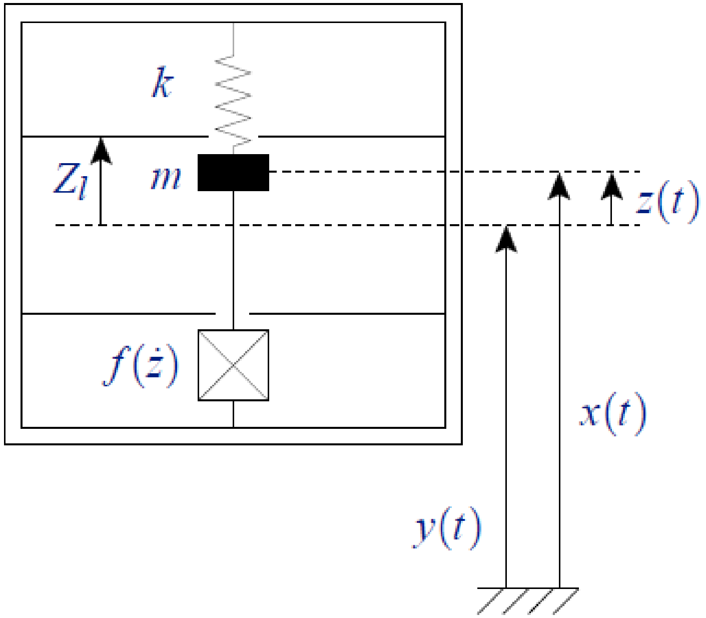
- Significant improvement in tuning of +/- 20% using sharp wedge
- Shape has major impact in tuning range

Power Electronics – Optimised Damping



- The energy harvesting system must have a power processor stage between the transducer and storage element – at least for rectification
- In Holistic, we have looked at circuits for both electromagnetic harvesters and piezoelectric harvesters

Inertial Generators



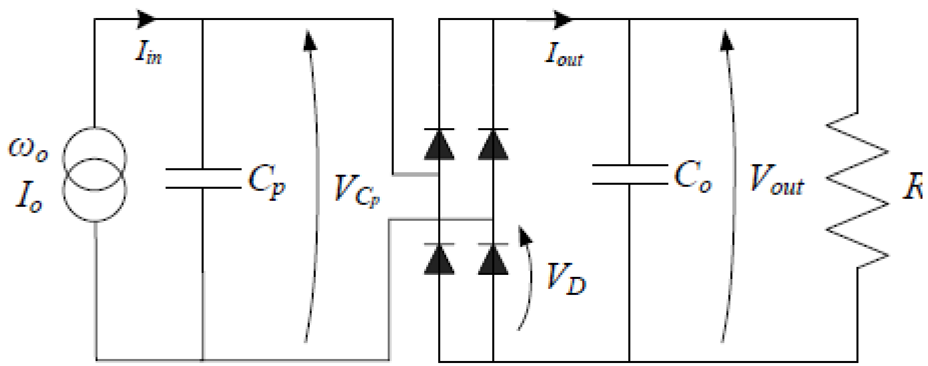
- We need to set the value of the damper to maximise the generated power.
- The optimal electrical damping maximises the force-distance integral of the damper
- Too low, no force
- Too high, no displacement

We have investigated circuits to optimise the damping

Piezoelectric Harvesters

Piezoelectric harvesters produce AC outputs

- Must have rectification
- May require step up or down depending on open circuit voltage of piezo.
- Simplest circuit we can think of is a full bridge rectifier:



Target is to achieve the optimal damping and rectify the signal simultaneously

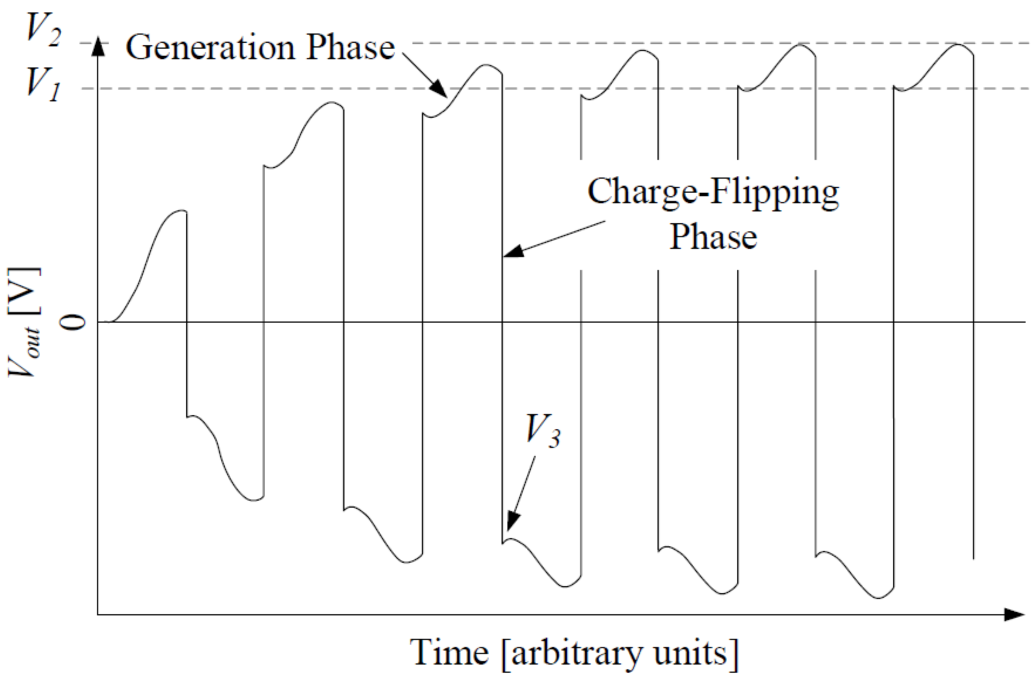
- Can we achieve optimal damping (maximum power) with this interface?

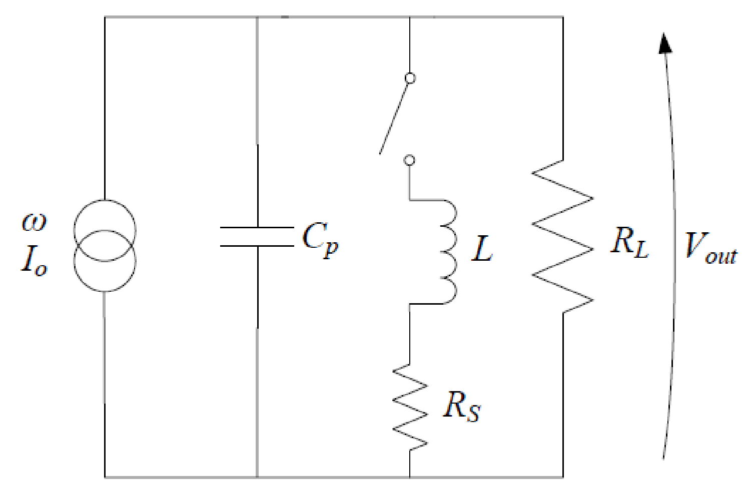
Imperial College London

holistic energy harvesting

Synchronous Switched Harvesting

Guyomar et al.



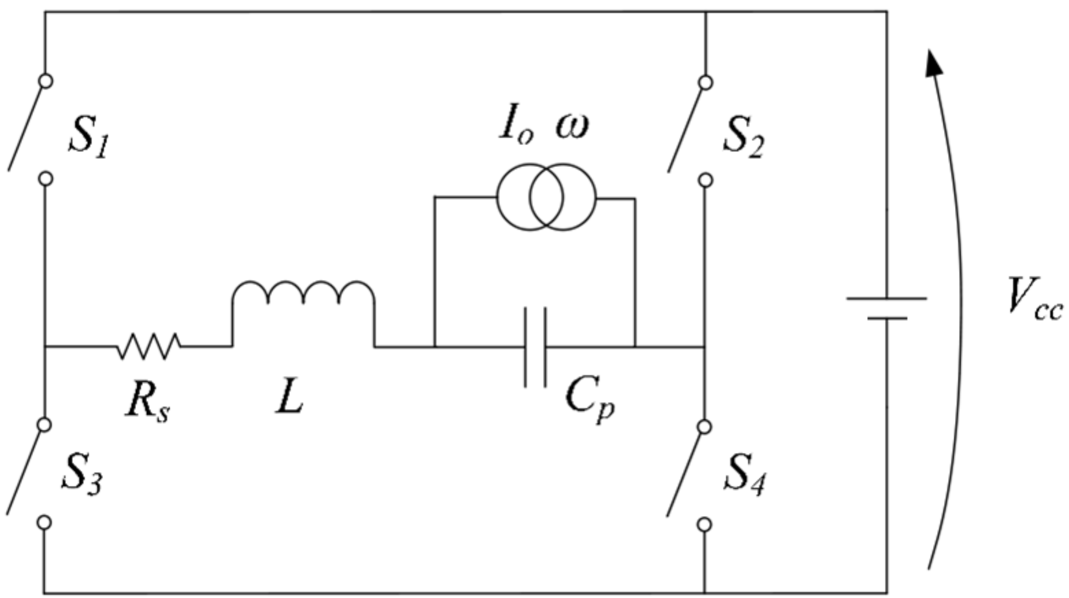


Often referred to as SSHI

- Charge on capacitor is resonantly flipped at voltage peaks to build piezo voltage
- Increases damping force and power

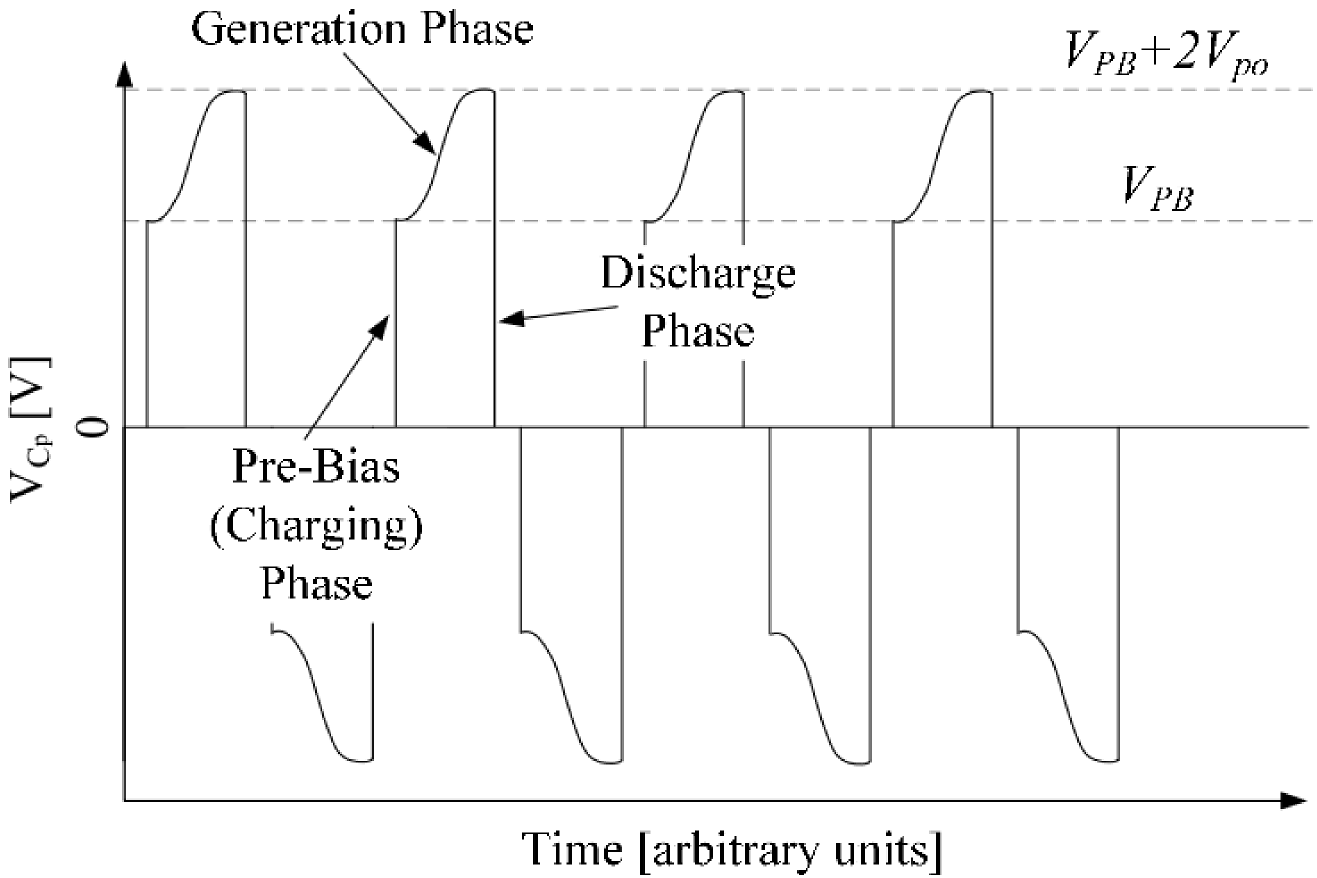
Single Supply Pre-biasing Circuit Overview

- Single source pre-bias circuit
- Source supplies pre-charge
- Generated energy returned to same source
- Can be made diode-less (with no free wheeling currents) if V_{CC} is optimally set



Let's see how it works...

Single Supply Pre-biasing Waveform



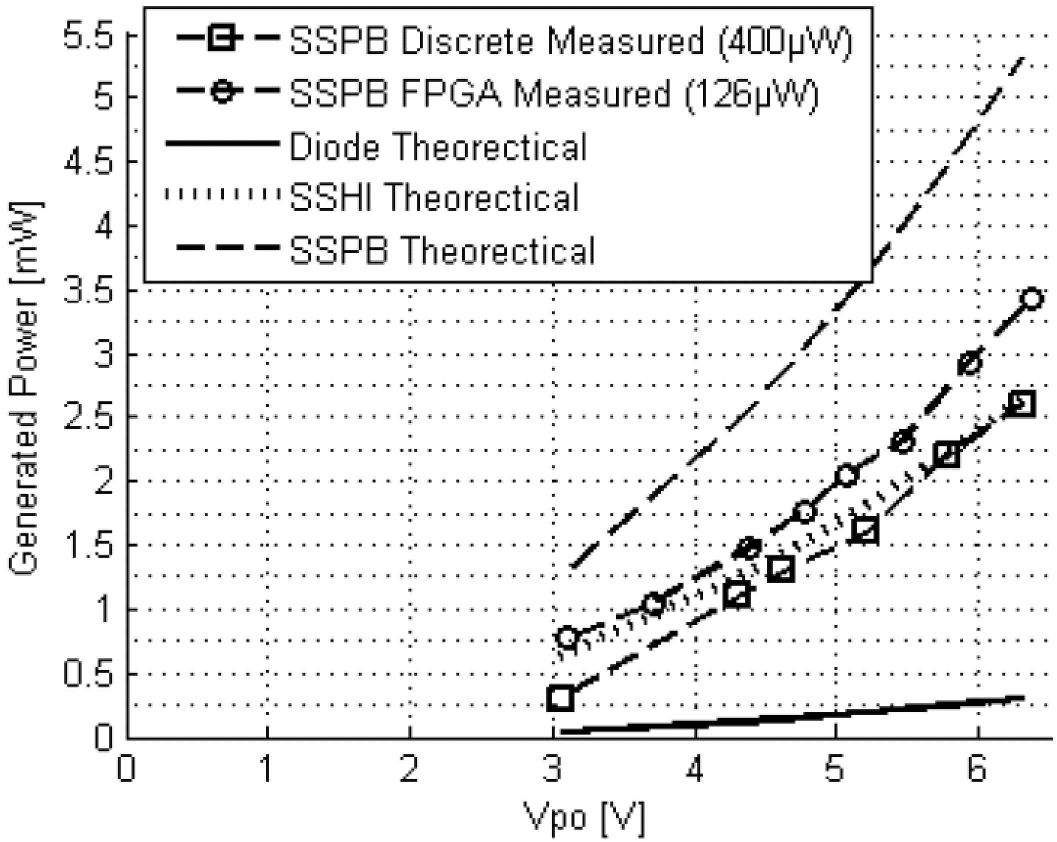
Operation similar to other synchronous circuits but charge "flipping" is in two stages

Power Output Formula

$$P_{\max} = V_{po}^{2} f_o C_p \left(\frac{8Q}{\pi} \right)$$

- V_{po} is the open circuit voltage of the piezo
- f_o is the mechanical excitation frequency
- Q is the quality factor of the resonant charging path
- C_p is the capacitance of the piezo

Power Comparison

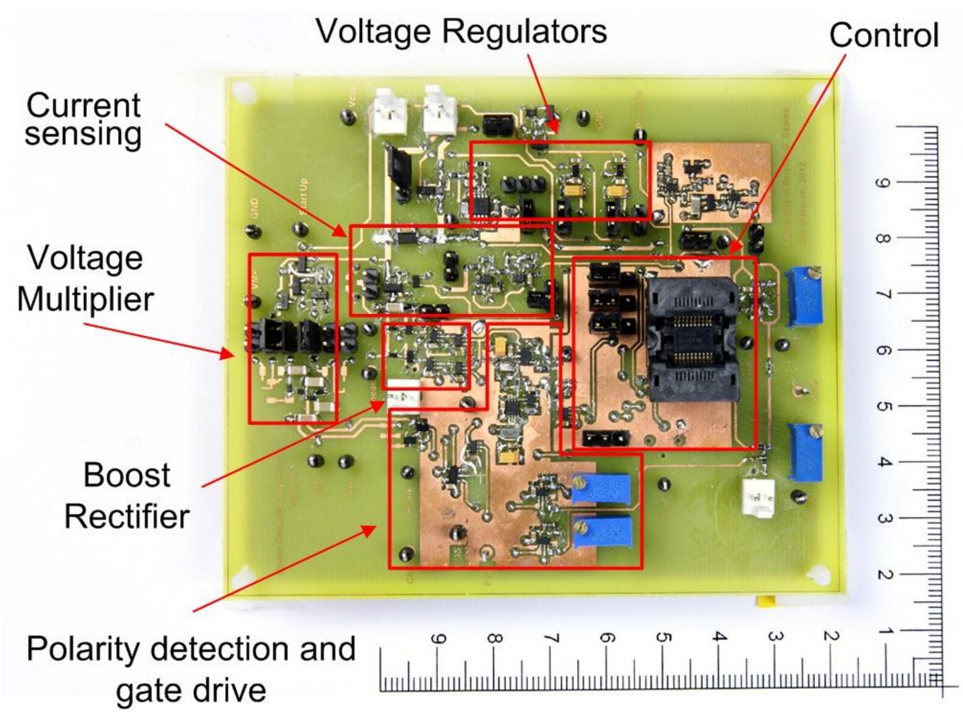


- Vast improvement over bridge rectifier
- SSPB practical implementation is better than the best possible performance of SSHI (even allowing for zero control overhead on SSHI)

For a review on all types of piezo interface circuits:

Dicken J, Mitcheson PD, Stoianov I, Yeatman, EM, ***Power-Extraction Circuits for Piezoelectric Energy Harvesters in Miniature and Low-Power Applications****, IEEE Transactions on Power Electronics, 2012, Vol:27, Pages:4514-4529, ISSN:0885-8993*

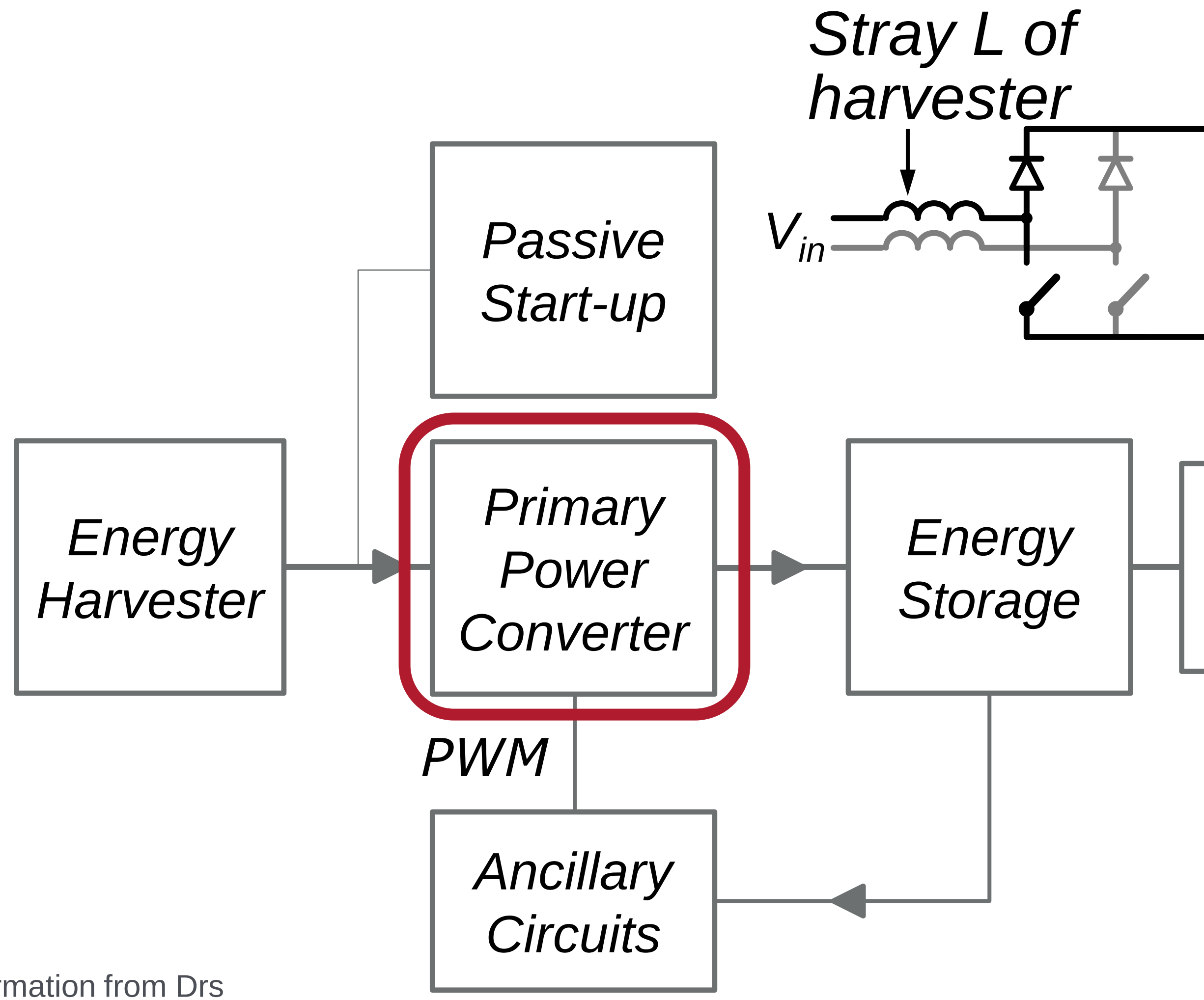
Interface Circuits for Electromagnetic Harvester



- Interface circuits and cold-start for electromagnetic harvester
- Implements MPPT through duty cycle control, altering the input impedance
- The MPPT cannot start from cold, some energy must be collected first
- Passive start-up-> active when running
- Power overhead of around 10-20μW when running

Information from Drs Stark/Burrow

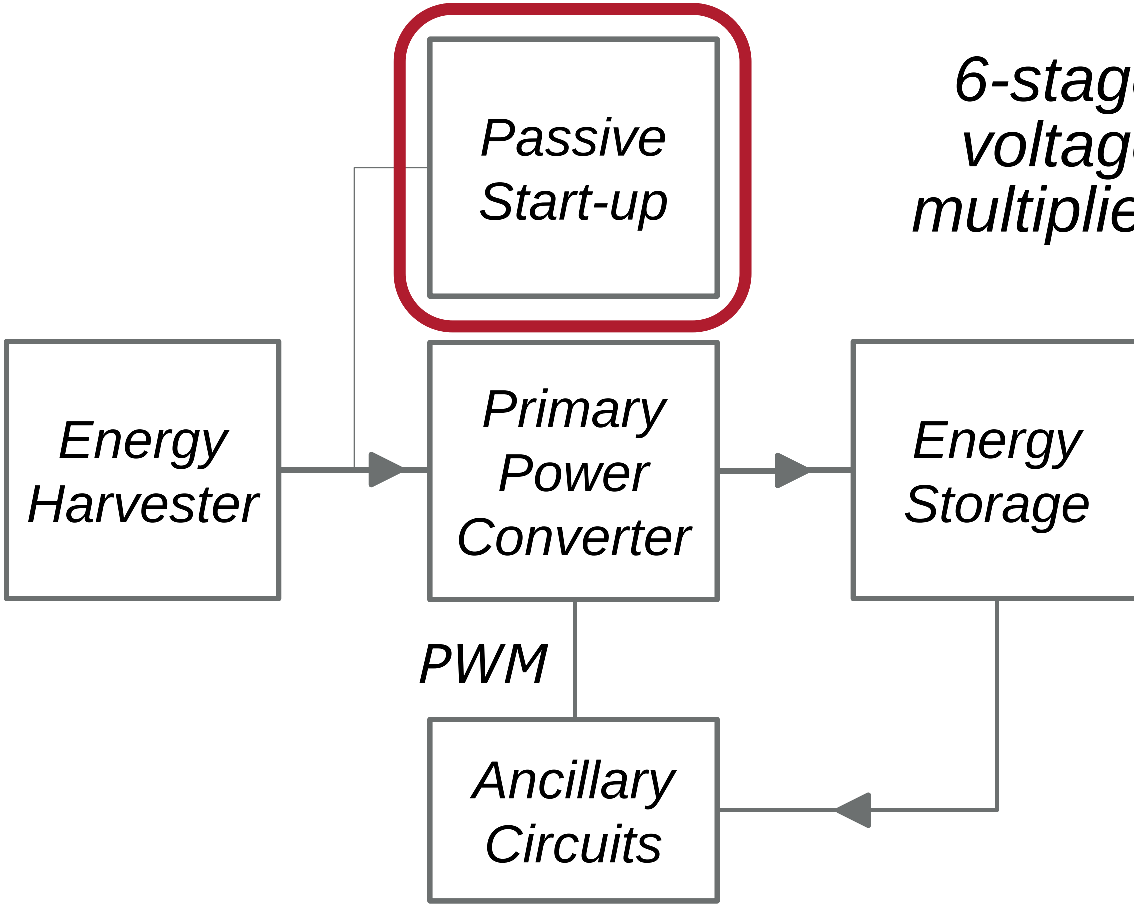
Low Power Implementation



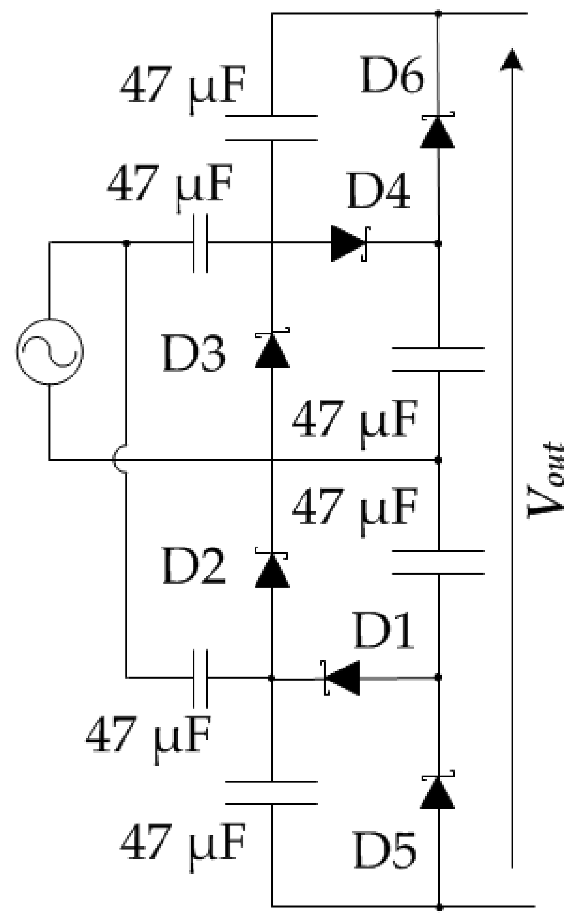
- *88 Hz alternating boost converters*
- *One switch at 30 kHz*
- *Requires polarity detection*

Information from Drs Stark/Burrow

Low-power implementation



6-stage voltage multiplier



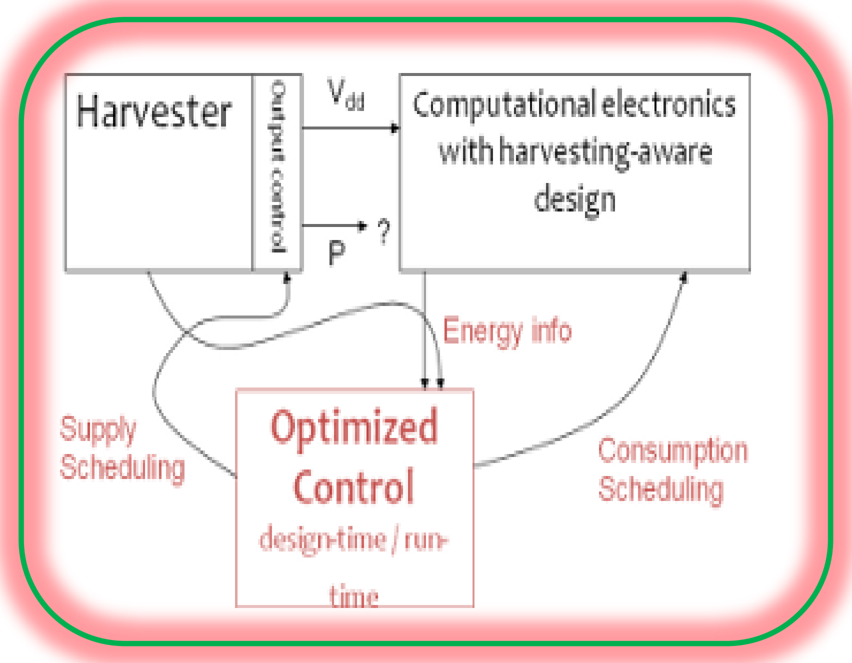
- *Voltage detector power-gates the μC*
- *μC controls activation of ancillary circuits and isolates voltage multiplier via JFET isolation switches*

Information from Drs Stark/Burrow

Energy Modulated Computation

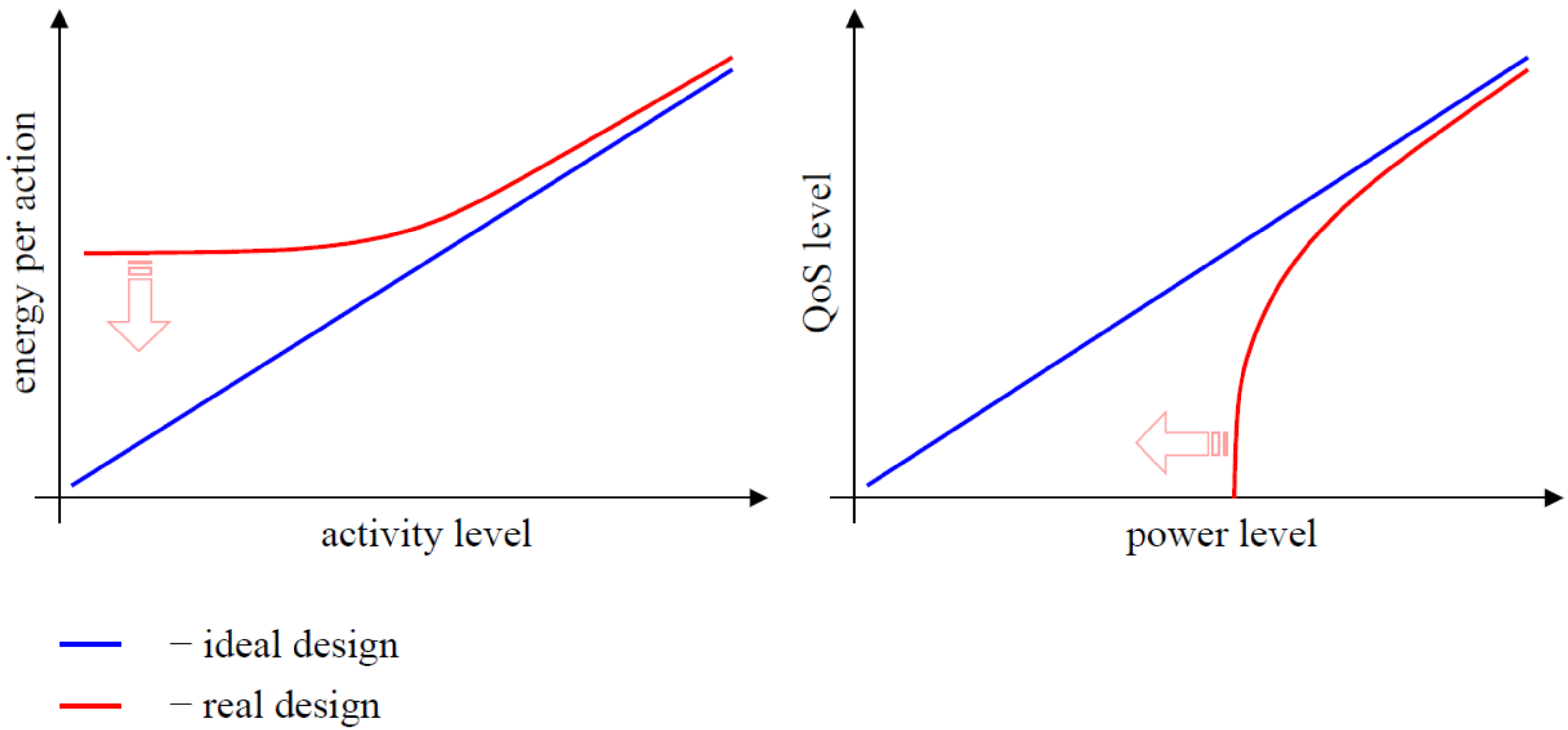
Vision, aims and objectives

- Energy harvester aware design methods for computational logic
- Capable of working under variable and unpredictable energy supply
- Circuit solutions for power control and management techniques
- Highly adaptive computational circuits



Information from
Prof Alex Yakovlev

Power Proportional Computing - limits



A. Yakovlev, Energy-Modulated Computing, Proc. DATE'11, Grenoble, March 2011, EDAA, pp. 1340-1345 (2011).

F. Xia, A. Mokhov, Y. Zhou, Y. Chen, I. Mitrani, D. Shang, D., Sokolov, A. Yakovlev, Towards power-elastic systems through concurrency management, IET Computers and Digital Technics, Vol.6, Iss. 1, pp.33-42, 2012.

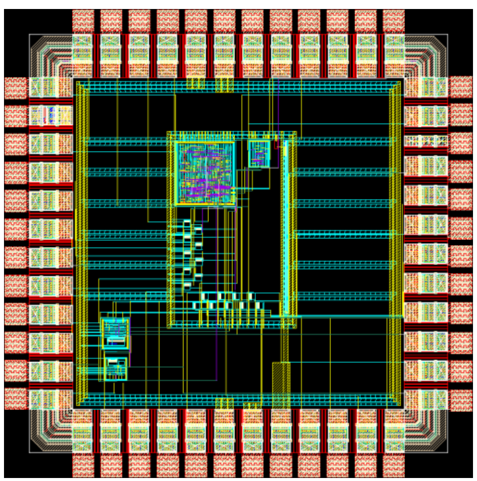
Let's have a look at a circuit building block that came out of this project

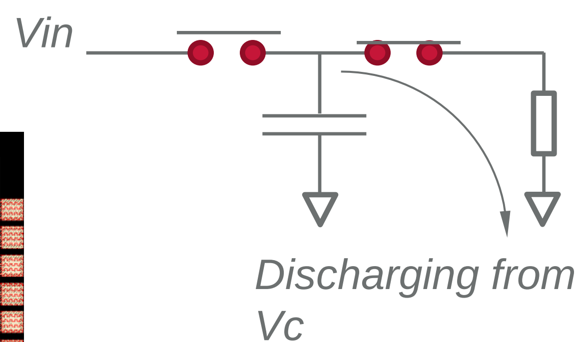
Information from
Prof Alex Yakovlev

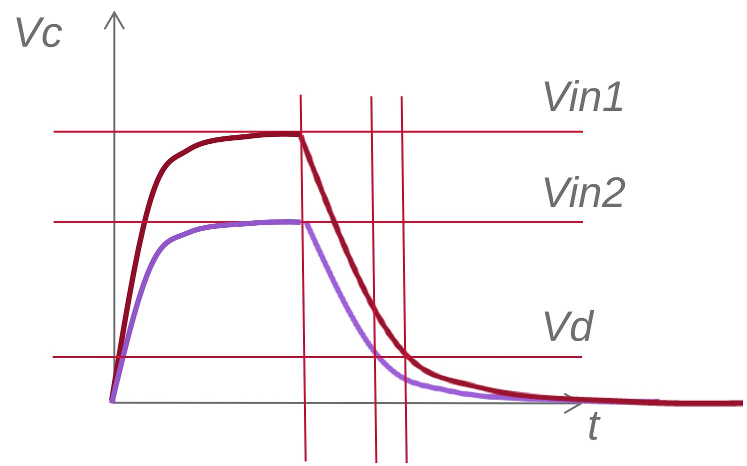
Charge-to-Digital Converter

Discharging until a certain Vd in order to get rid of timing reference

Voltage sensor chip: UMC CMOS 180nm







Vd is still a constant reference! But it does not have to be externally sourced. It could be based on some internal semiconductor characteristics

R. Ramezani, A. Yakovlev, F. Xia, J. Murphy D. Shang, "Voltage Sensing Using an Asynchronous Charge-to-Digital Converter for Energy-Autonomous Environments", IEEE Journal on Emerging and Selected Topics in Circuits and Systems (JETCAS), [in press].

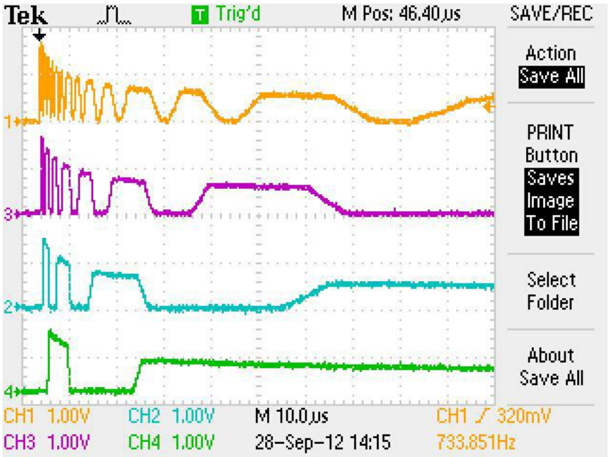
Information from
Prof Alex Yakovlev

Imperial College London

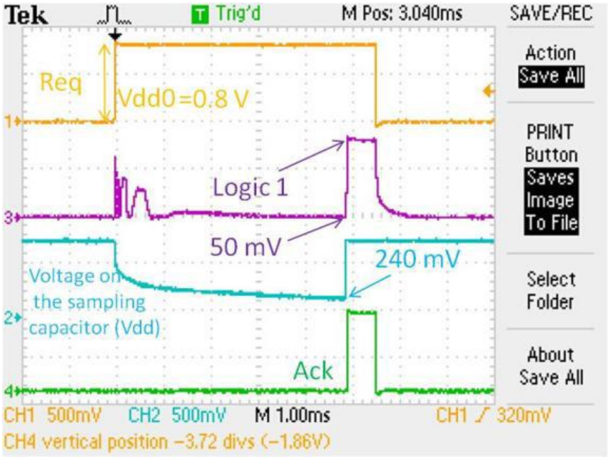
holistic energy harvesting

Voltage sensor chip results

Counting action:

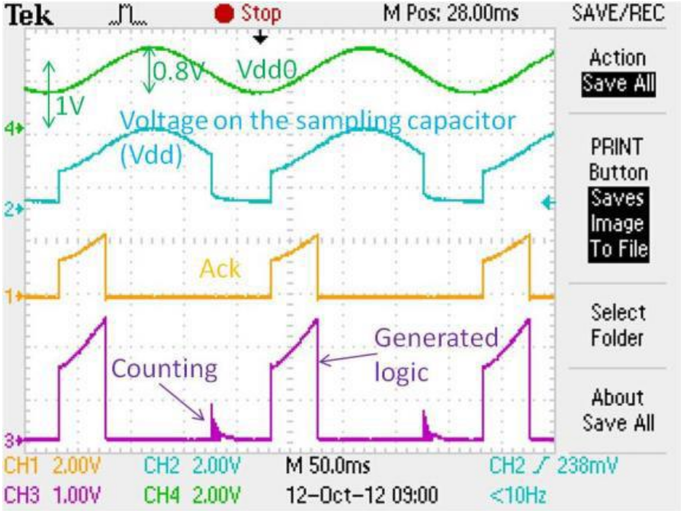


Reading the output:

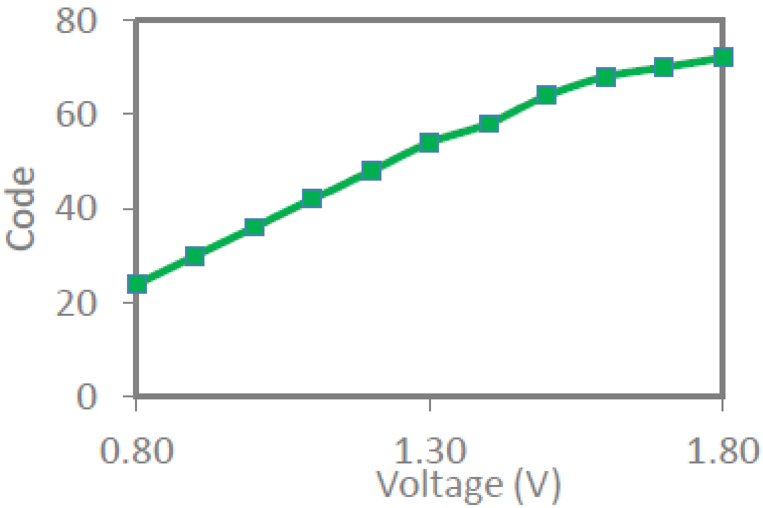


Information from Prof Alex Yakovlev

Sensor operation under variable voltage:



Output code in the counter:



System Modelling

Imperial College London

holistic energy harvesting

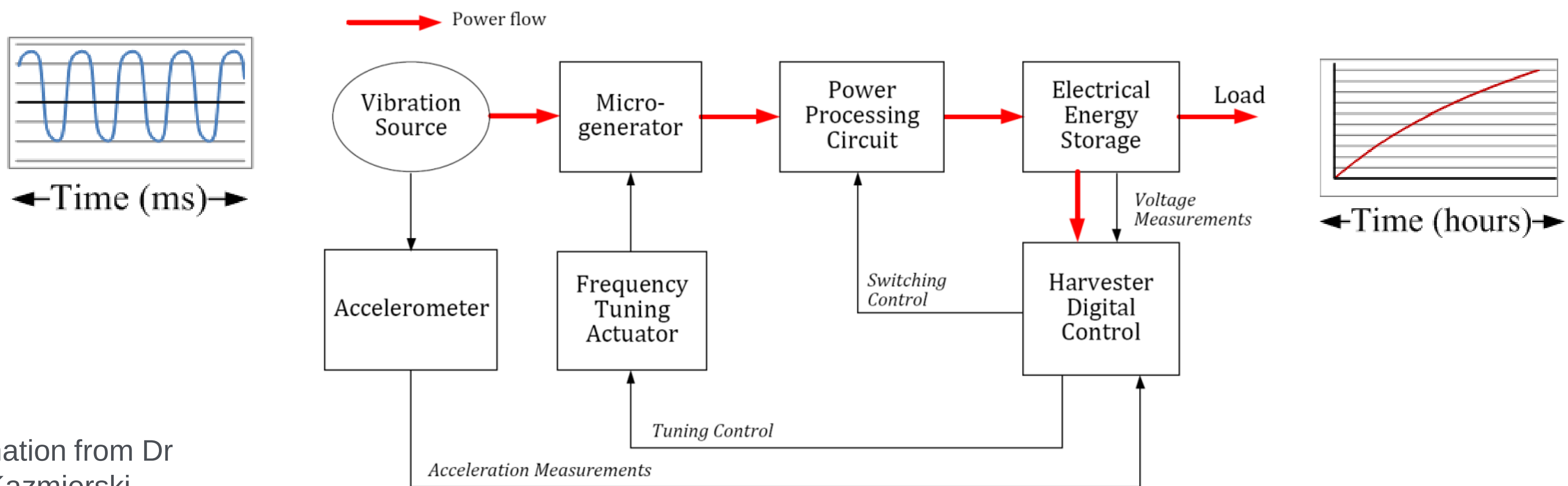
Why EH simulations are CPU intensive

Excessive CPU times due to disparate time scales

- High-speed microgenerator: small simulation time step (0.1ms)
- Low-speed storage: supercapacitor can take tens of hours to charge

Supercapacitor charging time is important

- It determines the system’s duty cycle



Information from Dr Tom Kazmierski

Linearised State-Space Techniques Used

Existing state-of-the-art simulators use implicit equation formulation:

$$\boldsymbol{f}(\dot{\boldsymbol{x}}(t), \boldsymbol{x}(t), t); \quad \boldsymbol{x}(0) = \boldsymbol{x}_0$$

State equations:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), t); \quad \boldsymbol{x}(0) = \boldsymbol{x}_0$$

State equations can be solved very fast

- explicit march-in-time process
- no Newton-Raphson iterations.

However, explicit solution can be numerically unstable if step size is too large.

- *State-of-the-art SPICE-like simulators do not use it.*

Information from Dr Tom Kazmierski

Exploring the Complete Design Space

Even with accelerated simulation – it still takes to long to optimise an EH system by multiple simulations

- A complicated system which has many parameters that can affect the system performance
- There are trade-offs between increasing and decreasing each of the parameters, energy generation vs. energy consumption

Utilised technique

- RSM model for fast design space exploration
- Optimisation of the RSM model using MATLAB
- Combination of the power of HDL in modelling multi-domain systems and the power of MATLAB in computation

Information from Dr Tom Kazmierski

Simulation Times

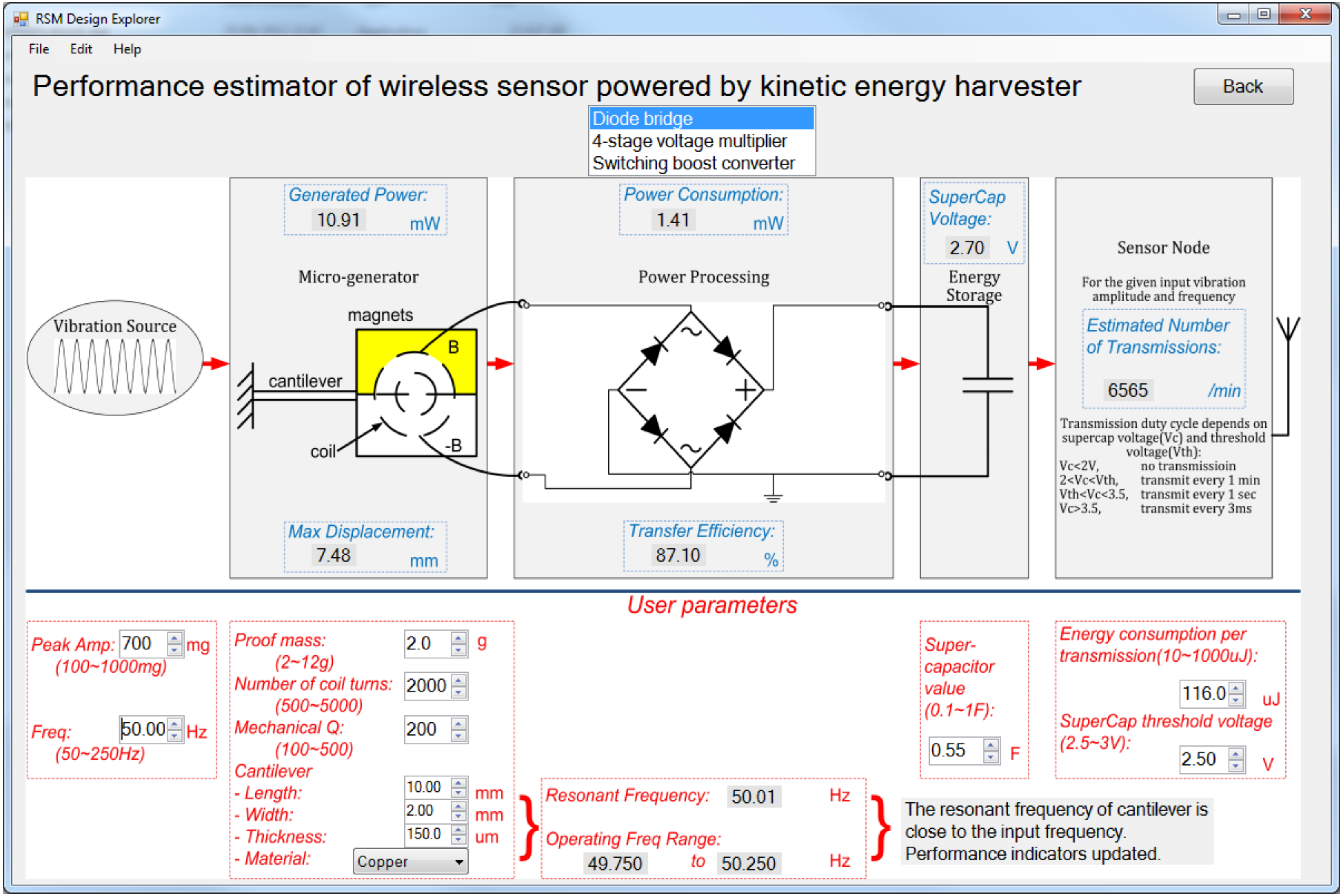
Comparison of CPU times

Two order of magnitude acceleration

	Existing technique		Proposed technique
HDL	VHDL-AMS	SystemC-A	SystemC-A
Integration method	Newton-Raphson based	Newton-Raphson based	Linearised state-space
CPU time for Scenario 1	2185 sec	2386	**20.3 sec**
CPU time for Scenario 2	7 hours	8 hours	**228 sec**

Information from Dr Tom Kazmierski

Simulation Tool GUI



Information from Dr Tom Kazmierski

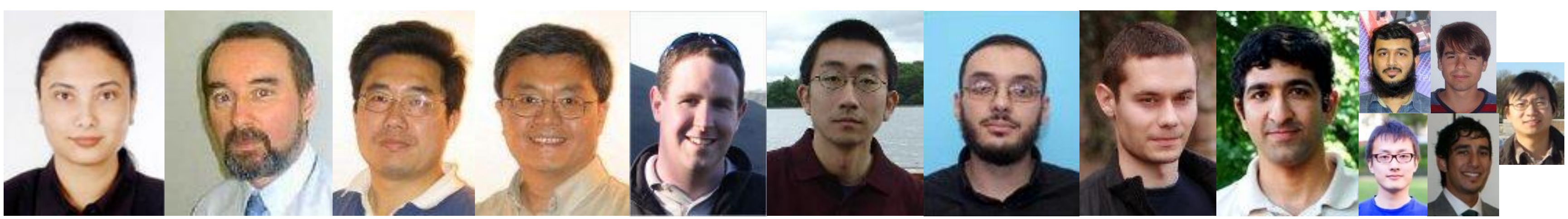
Conclusions

- Adaptive Harvesters
  - » MEMS VRD
  - » Magnetic potential well
- Power Electronics
  - » Optimal damping for piezoelecrics (SSPB)
  - » Optimal damping for electromagnetic harvesters (boost rectifier)
  - » Passive startup, and very low power overhead
- Energy Modulated Computing
  - » Asynchronous techniques
  - » Charge-to-digital converter
- System Modeling and Simulation
  - » Linear state-space models
  - » Response surface models

Acknowledgements

12 Investigators

14 Researchers



Acknowledgements

Work supported by EPSRC

Grant number EP/G070180/1

"Next Generation Energy-Harvesting Electronics: Holistic Approach"

Eric Yeatman, Bernard Stark, Bashir Al-Hasmimi, Tom Kazmierski, Alex Yakovlev, Geoff Merritt, Anisha Mukherjee, Steve Wright, Alex Weddell, Plamen Proynov, Gyorgy Szarka and all those involved in the project

http://www.holistic.ecs.soton.ac.uk

2013

PowerMEMS

United Kingdom, Dec 3rd – 6th 2013

PowerMEMS School Dec 2nd – 3rd

More information:
http://www.powermems2013.org

Join our Facebook Page:
http://www.facebook.com/PowerMEMS2013