ULTRA-TUNABLE MICRO-POWER CONVERTERS

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ABSTRACT

This paper discusses the challenges of micro-power conversion and management for autonomous Microsystems. Such systems hold enormous promise in both the military and commercial world due to their small size and numerous applications. However, at such reduced size scales, power conversion and control components are no longer trivial parts of the overall system. Depending on the desired functions included in a single microsystem, numerous powers and/or voltages may be required, but having multiple dedicated power converters becomes impractical. Here, we present a new concept for creating ultra-tunable micro-power converters by introducing a novel reconfigurable micro-scale transformer approach within traditional inductive boost circuits.

I. INTRODUCTION

Meso- to micro-scale autonomously operating mobile systems have the potential to provide huge improvements in tactical situational awareness to the U.S. Army's primary customer: the Warfighter. Such systems could access forbidden, remote, or traditionally inaccessible locations to collect a variety of relevant information while maximizing stealth and minimizing risk to the Warfighter. In this vein, the U.S. Army Research Laboratory recently started a Collaborative Technology Alliance on Micro Autonomous Systems and Technology, or MAST-CTA [CTA]. The goal of MAST is to enable enhanced tactical situational awareness in urban and complex terrain through the development of a collaborative ensemble of multifunctional, mobile Microsystems (approximately palm size and below). The four MAST focus areas are Micromechanics (making a small widget mobile), Autonomous Processing (coordinating between swarms of mobile widgets), Microelectronics (developing the electronic hardware, sensors, etc), and Integration (intelligently putting it all together). However, at this reduced size scale, the already formidable tasks facing each center are exacerbated by the limitations imposed by one overarching problem: Power.

When developing a power system for such a specialized system, designers must operate with two overriding concepts in mind: First, that *the size/weight of the power system directly effects system functionality* – one must avoid crushing your widget with a large power pack. This should go beyond reserving space for sources themselves to include ancillary components used to monitor and/or control their performance. The second necessary concept is *efficient power management and conversion*, which are essential to mission utility. The more power lost during 'sleep modes' or converting between voltages, the more power the widget must carry to perform its intended functions. While efficient conversion and control may seem an obvious goal, the difficulty of efficient power conversion as these systems shrink to the mm^3-scale is often overlooked.

This paper will analyze the complex challenge of developing intelligent and efficient power conversion components capable of spanning an ultra-wide output range for autonomous Microsystems. Section II will review basic power converter techniques. Section III will introduce some of the unique sources and loads in development for MAST-type systems. Section IV will analyze the tradeoffs in power converter design within such a size/weight constrained environment. Section V will introduce a new concept for creating ultra-tunable micro-power converters by introducing a novel reconfigurable micro-scale transformer. Section VI will describe one simulated design and the potential performance of boost converters using such devices, while Section VII will focus on future directions.

II. BASIC POWER CONVERTERS

The most straight forward converter techniques may be switched capacitor (SC) converters, since capacitors charged in parallel and discharged in series offer a simple method of voltage boost and can be easily implemented in CMOS. However, such topologies have

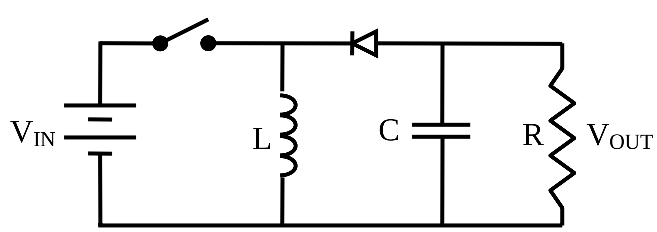

Figure 1: *Basic buck-boost converter.*

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Topology	Continuous Mode	Discontinuous Mode
Buck	$\frac{V_{OUT}}{V_{IN}} = D$	$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1+\frac{2L \cdot I_{OUT}}{V_{IN} \cdot D^2 \cdot T}}$
Boost	$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1-D}$	$\frac{V_{OUT}}{V_{IN}} = 1+\frac{V_{IN} \cdot D^2 \cdot T}{2L \cdot I_{OUT}}$
Buck-Boost	$\frac{V_{OUT}}{V_{IN}} = -\left(\frac{D}{1-D}\right)$	$\frac{V_{OUT}}{V_{IN}} = -\frac{V_{IN} \cdot D^2 \cdot T}{2L \cdot I_{OUT}}$

Table 1: *Ideal behavior of basic switched inductor DC-DC converters.*

limited voltage range (oxide breakdown), power handling (low capacitance per area), and high switching losses as they scale up (due to a larger number of switches). Switched inductor (SI) topologies, like that shown in Figure 1, typically use a single switch, single magnetic component, and often provide convenient voltage tuning and high efficiency across a wide range of powers and boost ratios. These advantages come at the expense of potentially difficult to integrate magnetic materials and magnetic property limitations/losses that may change with frequency. Assuming ideal components, the output voltage of basic SI converters in continuous / discontinuous modes can be easily derived and are shown in Table 1 (where *D*=duty cycle, *T*=on time, *L*=inductance, and I_{out}=average output current).

In practice, efficient SI boost converters are usually limited to ~5X voltage gain as extreme switch duty cycles introduce numerous loss mechanisms. For applications where >5X boost is desired, a "flyback" topology can be used (see Figure 2) where a transformer replaces the inductor in a buck-boost configuration and the voltage gain is determined by both the duty cycle and the turns ratio (1:n) within the transformer:

$$\frac{V_{OUT}}{V_{IN}} = n\left(\frac{D}{1-D}\right) \quad \text{(Continuous)} \quad (1)$$

For example, a flyback configuration could enable high boosts from a battery to the required voltages for piezo actuators by using a high turn ratio transformer.

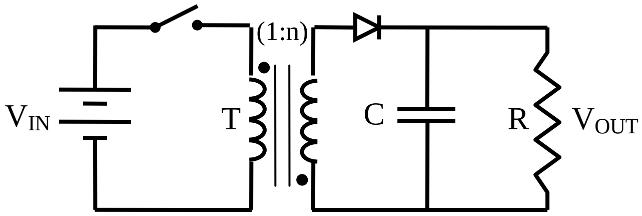

Figure 2: *Flyback boost converters can achieve high voltage step up using the turns ratio of a transformer (1:n), while fine voltage tuning is achieved by modulating the duty cycle (D) applied to the switch.*

III. MICROSYSTEM SOURCES / LOADS

A number of unique meso- to micro-scale mobile platforms have been proposed. In addition to the concepts presented in MAST, groups have started work on systems at the lower end of the size scale, such as the piezoelectrically-driven 60mg "Fly" developed by Robert Wood's group at Harvard [Wood], or the PZT-MEMS-based "scorpion" being developed by the Army Research Lab and University of Michigan [Oldham]. Given their goal of providing maximum utility to the Warfighter, it is desirable to integrate myriad sensors, actuators, and processing components onto a single system.

Figure 3 broadly illustrates some of the potential sources and loads that could be included on a candidate system. On the source side, to maximize system range and lifetime, not only will finite power sources like batteries be included, but energy scavenging will likely be added as complementary (but intermittent) power sources. On the load side, the possibilities are nearly endless. Some basic functionality can be envisioned with basic communications, sensing, processing, and actuation. Depending on their type and functionality, these devices range from high voltage / low current to high current / low voltage. Note that since batteries can be re-charged by energy scavengers, it may also act as a load.

IV. MICRO-CONVERSION & CONTROL

Currently, the most convenient and likely primary power source is a 3-5V thin film battery, an active area of research in itself [Bates]. However, many of the sensors or actuators will require vastly different voltages. For example, some have an interest in using dielectric elastomer actuators, which could require kilovolt-level outputs [Pelrine]. Conversely, low power processing researchers prefer low voltage operation (<0.3V) to minimize energy per operation [Hanson]. Thus, in addition to carrying a battery, the system must also carry

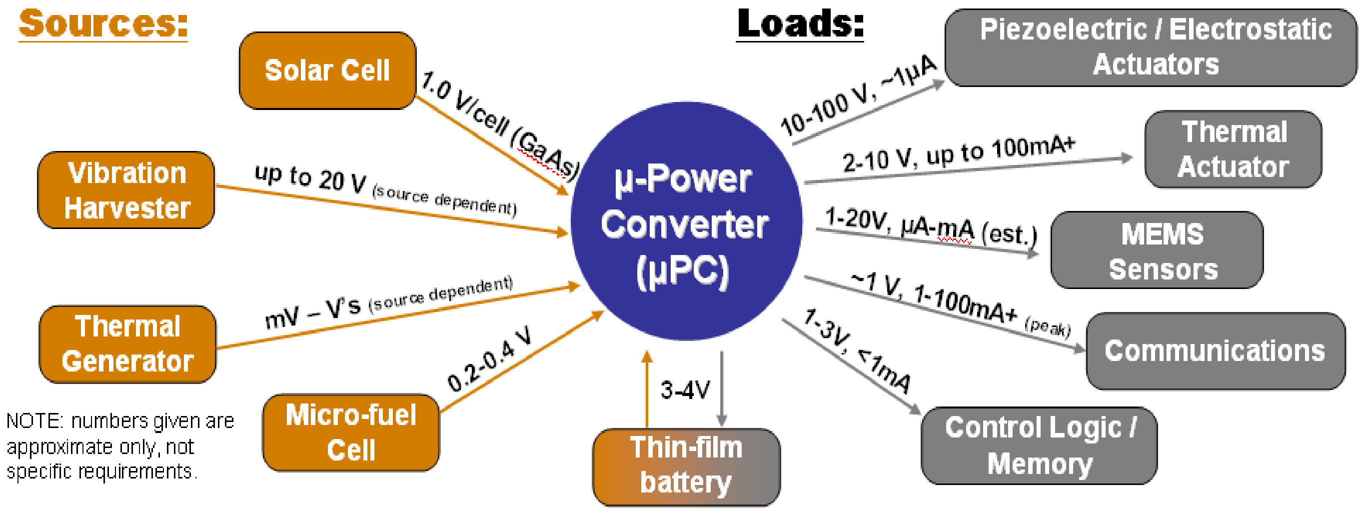

Figure 3: *Micro-scale autonomous systems will require micro-power converters capable of interfacing with myriad power sources & loads across a vast range of voltage & power levels.*

a power system capable of efficiently converting a 3-5V battery into a range of output voltages that could span 3-4 orders of magnitude. While fine voltage tuning can be accomplished with duty cycle control, a flyback converter for high voltage typically will not work for a low voltage application as well. Thus, each voltage range could require a separate power converter, and more importantly, separate passive components that add greatly to the size/weight of a system (or whose properties/efficiency may be compromised to accommodate space constraints). Given the size scale of these proposed systems, the micro-power converter (µPC) must be only a fraction of the total power unit to ensure minimal effect on mobility of the system. This leads to a target weight of only a few milligrams.

The limiting factor for scaling such power converters is the size/weight of passive components (inductors and capacitors), as the basic switch logic and control can be easily miniaturized (though high frequency and high voltage compliance are non-trivial). Furthermore, at this small size scale it may not be practical to have separate power converters with dedicated passive components for each output. These tradeoffs must be considered early during power converter design, with careful attention paid to the expected power usage profile. This challenge leads to an unusual paradigm to consider in this unprecedented size/weight constrained environment: can (or should) a mobile microsystem "Walk" and "Chew gum" at the same time? It may be that for practical purposes only one function is performed at a time, theoretically enabling a single power converter to be used if it can be operated across both regimes.

For example, let us consider a case where 2 different functions are desired: "walking" requires 50V of actuation and uses ~60mW of power, while "chewing" uses 30mW at 1.5V. Assuming a 4V battery as the source, and a switching frequency of 1MHz, a basic Buck-Boost converter (shown previously in Figure 1) was simulated in PSPICE for two different inductor values, 5µH and 50µH. For the "chewing" function, each inductor gave approximately the same conversion efficiency (~63%, limited by diode loss in this example). For the "walking" function, the 5µH inductor had a 61% efficiency, while the 50µH inductor resulted in a 90% efficiency.

At first glance, it looks like a 50µH would be the obvious choice for a converter because of its higher efficiency. However, one must remember that at this scale, a 10X larger inductor may have enough mass to decrease system mobility or even effect the power required to "walk." In addition, whenever the system is "chewing," the inductor is 10X larger than necessary. Figure 4 plots the net conversion efficiency achieved

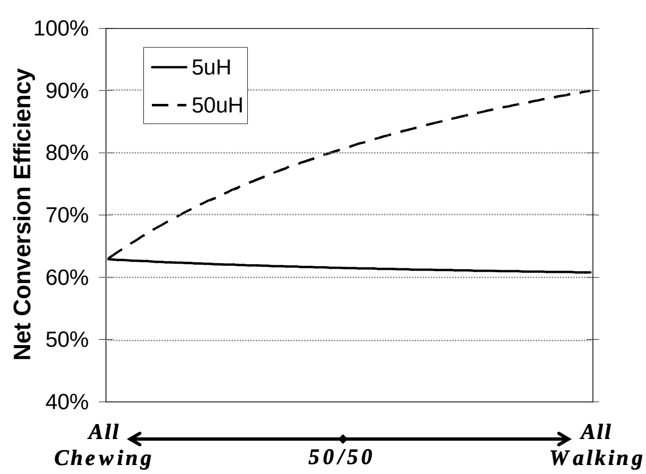

Figure 4: *Net electric conversion efficiency as a function of use profile ("Walking" with 50V at 60mW vs "Chewing" with 1.5V at 30mW) for a Buck-Boost converter (1MHz) with either 5µH or 50µH inductor.*

with converters based on either inductor size as a function of anticipated usage profile. If the system plans to "chew" far more than it plans to "walk," the improvement in net conversion efficiency would be small and the size benefit of a single small inductor could outweigh the rare improvement in "walking" conversion efficiency gained from the larger passive components. Conversely, if "walking" is the primary function, the larger inductor may be acceptable. Therefore, in this unprecedented size/weight constrained environment, custom micro-power conversion systems must be developed from the ground up to effectively balance the competing needs of both size and efficiency.

V. RECONFIGURABLE PASSIVES

By applying many of the fabrication techniques developed in the area of Microelectromechanical systems (MEMS), previous groups have demonstrated the ability to integrate thin film magnetic components within SI converters [Brunet, Ahn, Park, Yun]. However, each of these components are static in nature, with optimum operating points and limited flexibility. Thus, for a system where multiple high and low voltage loads across a range of power levels will be present, many separate power converters would be required and would add greatly to the size/weight of a system. In contrast, here we present a novel approach to micro-power conversion and control: the use of a single micro-magnetic transformer with the ability to mechanically reconfigure its turns ratio as a coarse voltage tuning mechanism to adapt to changing source-load configurations.

The concept of a MEMS-reconfigurable transformer is shown schematically in Figure 5. A set of conductor coils are microfabricated to loop around a thin film magnetic core (such as NiFe). "Taps" are periodically provided through a series of microelectromechanical (MEMS) switches. In the example, the set of 6 coils can be configured with either a 3:3 turns ratio (equivalent to 1:1 "zero boost" configuration) or a 5:1 ratio (providing a corresponding voltage boost). Fine voltage control would then be accomplished via duty-cycle adjustments.

Though a 1:1 to 5:1 tuning is shown in the figure, nearly arbitrary combinations are possible depending on switch/tap locations layouts. Also, the approach is not limited to simply transformers, tapped inductor or autotransformer concepts could be fabricated / developed in much the same way. This single reconfigurable magnetic component approach is ideal for size/weight constrained systems, enabling a single converter to be tuned across an ultra-wide range as the load demands (for either "walking" or "chewing"), while adding minimal weight to the system.

A critical factor in such a device is the switch mechanism used. It must be compatible with the magnetic component process flow, occupy minimal area, operate on low voltage (<5V), and draw nearly zero static power. Common MEMS actuator mechanisms considered, but so far discounted for early prototypes, include: electrostatic comb-drives [Legtenberg] due to their large gaps and high voltages, piezoelectric benders [Polcawich] due to the complex additional processing, and thermal actuators [Que] due to their high constant current draw. Electrostatic actuators based on parallel plate attraction are attractive due to their simplicity and flexible design space. In addition, using torsional suspension actuators [Xiao] for the switch arm, such as that shown in Fig 6, enables excellent rotational compliance, lowering their operating voltage. Fig 7 shows the calculated pull-in voltage [Xiao] as a function

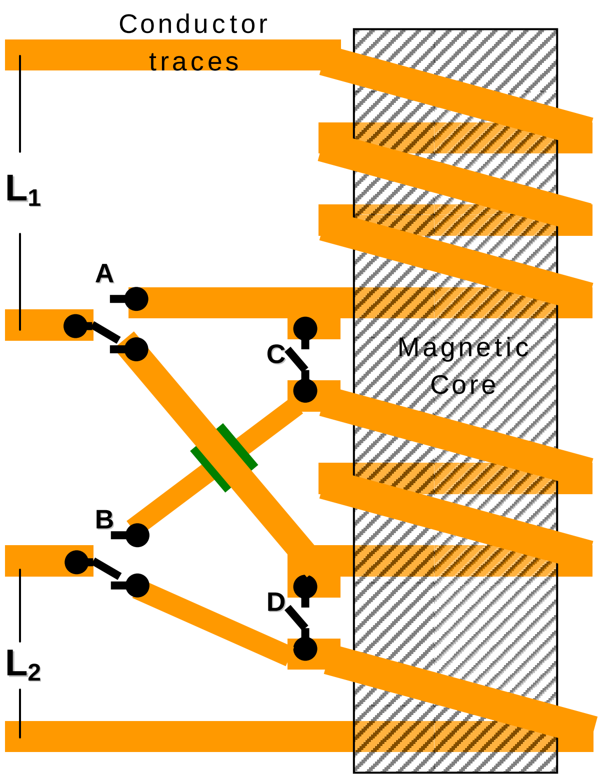

Figure 5: *Example layout of a MEMS reconfigurable transformer. In this example, the micromechanical switches are used to physically connect 6 loops around a magnetic core in two different configurations resulting in turn (or L_1:L_2) ratios of either 1:1 or 5:1.*

Switch	***L_1:L_2 =1:1*** *(Isolation)*	***L_1:L_2 =5:1*** *(Boost)*
A	Up	Down
B	Up	Down
C	Open	Closed
D	Closed	Open

Table 2: *Switch positions for either configuration of the dynamic transformer.*

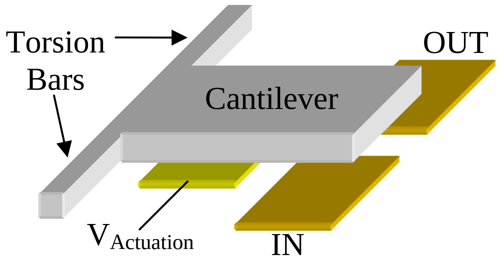

Figure 6: *Torsional cantilever actuator as a contact switch for reconfiguring transformers.*

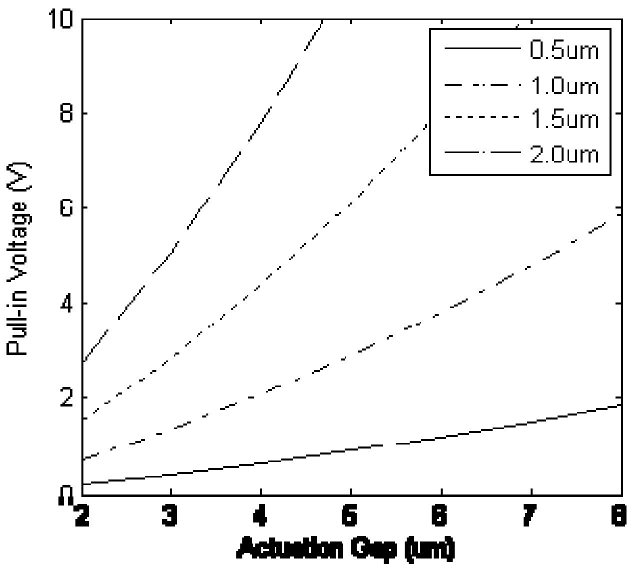

Figure 7: *Calculated pull-in voltage for a 100µm gold cantilever torsion actuator with different thicknesses (supports are assumed to be 10µm wide by 20µm long).*

of actuation gap for different gold cantilever thicknesses. Gold films 1-2µm thick are reasonable for gaps of a few microns (easily achievable with sacrificial photoresist layers) and meet the desired <5V level, while providing sufficient current carrying capability. Static power draw is also limited to leakage currents through the dielectric layer, which are anticipated to be in the µA range.

VI. CONVERTER DESIGN & SIMULATION

In order to estimate transformer performance, one must first outline a set of fabrication guidelines and propose a process flow that will constrain our component dimensions. A preliminary process flow is outlined in Figure 8.

The magnetic material is assumed to be sputtered nickel-iron (81% Ni / 19% Fe target acquired from Kurt J. Lesker Co, post-deposition properties measured at ARL). Windings are assumed to be either sputtered or electroplated copper, with aspect ratios conservatively

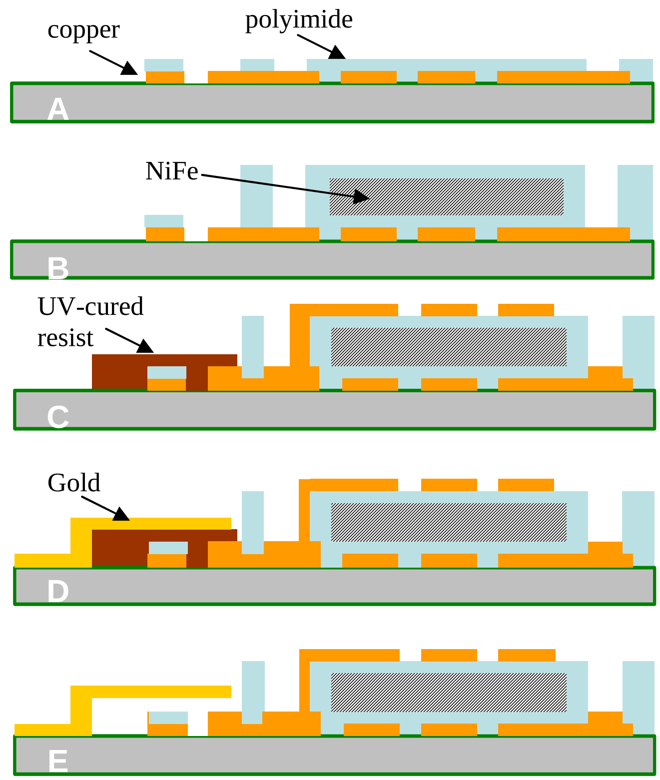

Figure 8: *Proposed process flow for integrating torsional cantilever switches with solenoid-like magnetic components. (A) Deposit/ pattern bottom conductor layer (Cu), and photo-definable polyimide as an inter-level dielectric. (B) Sputter deposit magnetic core using shadow mask, and cover with second polyimide layer. (C) Define sacrificial photoresist layer, where UV-curing prevents removal during an acetone lift-off of the gold cantilever during (D). Finally, in (E), an oxygen plasma is used to release the cantilever switch.*

limited to 1:1 by photolithography. Material thicknesses are limited by skin depth constraints to avoid significant eddy current losses. Initial analysis was performed using an operating frequency of 10MHz that was chosen as a compromise between the desire for fast switching and the anticipated reduction in material performance at higher frequencies.

Due to the desire for minimal area/weight, the initial prototype design described later was limited to <5mm^2 for the entire transformer. The exact weight is then determined by wafer thickness, which ideally could be thinned down to ~100µm without any difficulty, leaving total weight in the couple milligram range.

Test NiFe films were magnetron sputtered at room temperature using a pulsed DC source in an Argon plasma. The relative permeability was measured using alternating gradient magnetometer (AGM) to be ~250 (slightly lower than expected) and the resistivity was measured using 4-pt probe to be ~30µΩ-cm. This leads to a skin depth in NiFe at 10MHz of approximately 3µm.

Therefore, the NiFe thickness used for our initial design was limited to 5µm. Saturation magnetization for these films was measured to be ~0.85T.

The core of the toroid-like transformer was limited to a ~2 by 2mm area with a ~500µm by 500µm hollow center. Four integrated electrostatic torsion switches would occupy an area <0.2mm^2, so even with routing lines etc, a minimal size/weight penalty is incurred for the extreme tunability offered by the ability to mechanically reconfigure the windings.

The size and layout of the core/windings is a non-trivial task as one must carefully balance total resistance, desired inductance, as well as saturation currents. Application considerations for max size, power handling (proportional to core volume), or resistance or inductance matching will also impact exact winding choices. Initially, the layout being considered here is essentially a solenoid, so the inductance (L) and saturation current (I_{sat}) can be written as:

$$L = \mu_r \mu_0 \left(\frac{N}{l} \right)^2 l \cdot A \qquad (2)$$

$$I_{Sat} = \left(\frac{l}{N} \right) \frac{B_{Sat}}{\mu_r \mu_0} \qquad (3)$$

where μ_0=permeability of air, μ_r=relative permeability, N=total number of turns, l=length of solenoid core, B_{sat}=saturation flux density of magnetic material, and A=cross sectional area of magnetic core.

The inductance and the saturation current are interrelated because the rise in current with time (di/dt) is determined by the input voltage to the converter (v_i) and the inductance:

$$\frac{di}{dt} = \frac{v_i}{L} \qquad (4)$$

But the absolute change in current (di) must not exceed I_{sat}. So for a particular frequency (i.e. dt), there is a minimum inductance required to prevent saturating the magnetic material. Substituting into (4) and rearranging:

$$v_i = \frac{N \cdot B_{sat} \cdot A}{dt} \qquad (5)$$

Thus, for a given input voltage and frequency, one must have high magnetic saturation, large magnetic cross sectional area, and a sufficient number of turns. For MEMS-fabricated magnetic components, A is typically small, so N must be large and dt small (high frequency). Obviously, high B_{sat} materials are a desirable starting point, but can only be increased so much before catastrophically effecting other magnetic or electrical properties. Methods for laminating such films to increase A are of course of high interest, with fabrication practicality being the limiting factor. When laying out the windings, generally larger N means increased resistance either through (a) longer cores (R↑,L↑ linearly) or (b) higher turns/length (R↑,L↑ quadratically for a fixed conductor aspect ratio). Since R and L track evenly for a particular conductor aspect ratio, in order too maximize quality factor (Q = ωL/R), high aspect ratio copper electroplating techniques are desirable.

An example system has been laid out to illustrate the range of values to be expected with this technology. Square copper windings 10µm in width with equal spacing were assumed (and should be easily achievable with electroplated copper), resulting in ~24 turns/480µm on each of 4 sides of the square transformer. In a basic 1:1 transformer configuration (N_1:N_2=48:48), this leads to a primary inductance of ~3µH, a winding resistance of ~25Ω, and an anticipated quality factor >7. Power handling meanwhile is estimated at >40mW before magnetic saturation.

An ultra-tunable power converter is then created by combining/cross-connecting the low voltage switches and tapped transformer. Gross tuning is achieved by re-arranging the 96 total turns into a step-up or step down transformer of nearly any pre-determined combination. Fine tuning would still be achieved via duty cycle control. The reconfiguration can follow that outlined previously in Fig 5, where some turns would actually change from primary to secondary winding. With this method, boost ratios >15:1 (N_2:N_1=90:6:) are reasonable to expect, ideal for driving many of the high voltage actuators being developed for MAST systems. Depending on the application / system being powered, reconfigured states could easily be 2:1 (64:32), 1:2 (32:64), 1:15 (6:90), or practically anything in between.

Alternatively, the MEMS switch could be used to simply 'short out' a number of turns in order to change their ratio. This technique leads to lower core utilization, but potentially requires less switches. In certain cases it also may hurt/help with matching inductances and resistances in the circuit. MEMS switches could also turn the magnetic core into a multi-tapped transformer or single large inductor depending on the application.

VII. CONCLUSION & FUTURE WORK

The paper has introduced the challenges faced in developing micro-power conversion and control mechanisms for mobile Microsystems. The concept of MEMS-enabled reconfigurable micromagnetic elements was introduced, along with a proposed fabrication approach, to accommodate the numerous source/load combinations likely in these systems. Ultra-tunable switched inductor converters were subsequently designed and analyzed using preliminary material characterization and fabrication guidelines. Our calculations indicate that 40mW converters with variable boost ratio's from <1:1 up to >15:1 appear feasible, but exact performance will be dictated by application considerations like size limits and power levels. It was also emphasized that size constraints and expected load profiles should be considered simultaneously as one must balance tradeoffs in hardware design, MEMS switch integration, and fabrication constraints.

Future work is focused on fabrication and testing of these reconfigurable passives within basic switched inductor power converters. Though electrostatic torsion switches are being initially developed, and should be low power, they still draw a finite amount of current even when they are not switching. As a next step, bi-stable MEMS switches are being investigated as a truly zero on-power switching mechanism [Qiu].

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