Towards Optimal Kinetic Energy Harvesting for the Batteryless IoT

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Abstract—Traditional Internet of Things (IoT) sensors rely on batteries that need to be replaced or recharged frequently which impedes their pervasive deployment. A promising alternative is to employ energy harvesters that convert the environmental energy into electrical energy. Kinetic Energy Harvesting (KEH) converts the ambient motion/vibration energy into electrical energy to power the IoT sensor nodes. However, most previous works employ KEH without dynamically tracking the *optimal* operating point of the transducer for maximum power output. In this paper, we systematically analyze the relation between the operating point of the transducer and the corresponding energy yield. To this end, we explore the voltage-current characteristics of the KEH transducer to find its Maximum Power Point (MPP). We show how this operating point can be approximated in a practical energy harvesting circuit. We design two hardware circuit prototypes to evaluate the performance of the proposed mechanism and analyze the harvested energy using a precise load shaker under a wide set of controlled conditions typically found in human-centric applications. We analyze the dynamic current-voltage characteristics and specify the relation between the MPP sampling rate and harvesting efficiency which outlines the need for dynamic MPP tracking. The results show that the proposed energy harvesting mechanism outperforms the conventional method in terms of generated power and offers at least one order of magnitude higher power than the latter.

Index Terms—IoT, Wearable, Batteryless, Kinetic, Energy Harvester, Power, Vibrations, Maximum Power Point, Frequency

I. INTRODUCTION

The IoT is identified as one of the major technologies impacting various applications including healthcare, agriculture, transportation, smart homes and more, by enabling countless sensors to collect and exchange data for smarter and more effective decisions [1]. However, current IoT sensors mostly rely on batteries for their continuous and uninterrupted operation. Batteries are bulky, expensive, hazardous and have limited charge/discharge cycles which impedes the pervasive deployment of IoT devices [2]. As a way of tackling these challenges, energy harvesting from ambient sources such as solar, kinetic, thermal and radio frequency waves has been used to convert the environmental energy into electrical energy to power batteryless IoT sensors without human intervention [1]. With recent technological advancements in micro-electro-mechanical systems, energy harvesting can enable per-
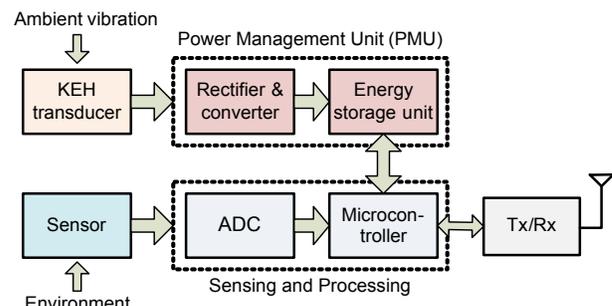

Fig. 1: Energy harvesting mechanism to power the IoT nodes

petual operation of IoT sensor nodes which is the key for realising a truly pervasive, batteryless IoT.

Kinetic Energy Harvesting is an attractive option to power IoT devices by converting the ambient vibration, motion and mechanical energy into electrical energy. A Power Management Unit (PMU) is used to manage the harvested energy [3] to power a load (or a node) as depicted in Fig. 1. The harvested energy is stored in an energy storage unit (i.e., a capacitor/battery) which is used to power a sensor node. The harvested energy is consumed by various hardware components within the sensor node including the sensor module, Analog-to-Digital Converter (ADC), microcontroller and transceiver to sample the physical attribute as well as its transmission to the destination/server. Depending upon the application, the harvested energy can be sufficient to power the sensors without the need of any external, depletable energy source, enabling Energy Neutral Operation (ENO).

Piezoelectric transducers are often used to power the sensors in human-centric IoT applications including human activity recognition and transport mode detection. In order to harvest maximum energy from the transducer, it must operate at its MPP, which is an operating point of the transducer where it offers highest power. Although, MPP tracking has been used in KEH [4] to increase harvested energy, it has not been systematically compared with the conventional design in terms of harvested energy. In addition, the dynamic tracking of MPP of the KEH transducer is still unexplored. Furthermore, there is no detailed study to compare the performance of the energy
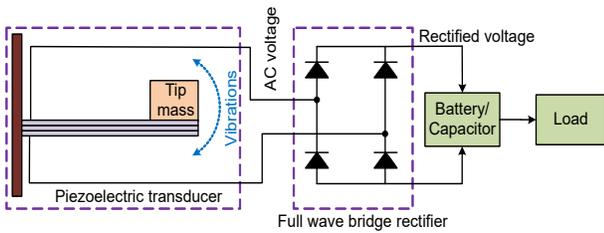
Fig. 2: General piezoelectric energy harvesting circuit

Fig. 3: Capacitor voltage in intermittently powered sensors

harvesting circuits with and without MPP tracking of the KEH transducer under a wide set of conditions typically found in human-centric applications.

In this paper, we explore the operation of a KEH transducer at the MPP using a DC-DC boost converter under vibration patterns that are typical for human-centric IoT applications. A DC-DC boost converter consumes some energy during its operation which may impact the overall efficiency compared to a converter-less design. In this document, we refer to DC-DC boost converter as DC-DC converter and converter interchangeably. In contrast to [4], we outline the need for dynamic MPP tracking and analyze the performance of both converter-less and converter-based energy harvesting designs. In order to conduct a fair comparison, we perform the experiments in a controlled environment using a stable load shaker whose vibration frequency and amplitude can be adjusted manually. We study the relation between harvesting efficiency and MPP sampling rate which outlines the need for real time dynamic MPP tracking. The results show that by operating the transducer at its MPP, the converter-based mechanism harvests, on average, at least one order of magnitude higher power, than the conventional converter-less design, depending on the vibration amplitude.

The main contributions of the this paper are given as:

- We analyze the dynamic electrical characteristics of a KEH transducer and explore its MPP.
- We design two hardware circuit prototypes; converter-less and converter-based, to explore the impact of MPP tracking using a DC-DC converter.
- We perform an experiment in a controlled environment using a stable load shaker and find that the proposed converter-based circuit harvests, on average, one order of magnitude higher power than the conventional converter-less design due to its operation at MPP.

The remainder of the paper is organized as follows. Section II discusses selected KEH-powered IoT devices and Section III describes the two energy harvesting design considered in this study. The prototyping and experimental setup is described in Section IV. Section V explores the MPP of the KEH transducer and provides the results. Finally, Section VI concludes the paper and outlines directions for future research.

II. RELATED WORK

In batteryless IoT nodes, energy harvesters are employed to provide unceasing energy for their operation. Zhao et al. [5] design a KEH based shoe to harvest energy from human motion. Their prototype harvests $1\,\mathrm{mW}$ of power while walking at
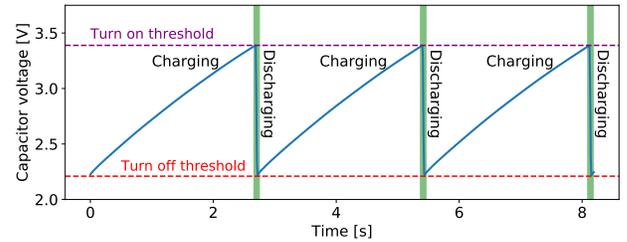
a frequency of about $1\,\mathrm{Hz}$. Their work shows the feasibility of using energy harvesters to power batteryless wearable devices. The authors of [6] design a KEH based wearable device to be placed on the wrist to harvest energy from human motion. As human arms offer lower vibrations compared to legs, they harvest $280\,\mu\mathrm{J}$ of energy during small human movements. Ryokai et al. [7] design a KEH based wearable device for children to harvest energy from their movements. The harvested energy from the wrist based wearable devices is used to blink an Light Emitting Diode (LED) in order to inspire the children to learn about energy and its transformation from one form to another. Olivo et al. [8] propose a fast start-up mechanism for wearable sensors using KEH. They employ a boosting circuit to step-up the harvesting voltage to power the wearable nodes. Authors in [9] employ KEH to harvest energy from human movements to power the wearable devices. They design backpack-based and insole-like harvesters which generate sufficient energy to power the on-body nodes. Xiang et al. [10] use a KEH transducer to harvest energy from the air flow of indoor Heating, Ventilation, and Air Conditioning (HVAC) system. The harvested energy is used to transmit air flow speed data to the server. Kuang et al. [4] employ KEH to harvest energy from human motion. They design a KEH hardware which operates multiple transducers at their MPP to harvest higher energy to power the body sensor nodes.

Some of the previous works [6], [8], [10] employ DC-DC boost converters in the KEH circuits to harvest higher energy for IoT nodes. However, they do not explore the MPP of the KEH transducer which is challenging due to the rapid changes in its output power. The authors of [4] do not consider dynamic tracking of the MPP under a wide set of conditions typically found in human-centric applications. Furthermore, to the best of our knowledge, there is no detailed study that compares the performance of MPP for KEH with conventional energy harvesting mechanisms for miniaturized IoT sensor nodes. This papers presents the operation of a KEH transducer at the MPP to harvest higher energy and compares its performance with the conventional converter-less energy harvesting circuit under a wide set of conditions typically found in human-centric applications.

III. KINETIC ENERGY HARVESTING

There are three mechanisms for converting the kinetic energy to electrical energy: piezoelectric, electromagnetic and electrostatic [11]. Piezoelectric is the most popular choice
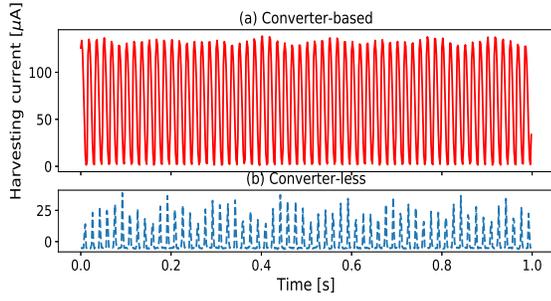
Fig. 4: Harvesting current in converter-less and converter-based circuits at the resonance frequency of the transducer

for wearable applications due to its simplicity and compatibility with micro-electro-mechanical systems. We discuss the functionality of a piezoelectric transducer and analyse the corresponding energy harvesting circuits in the following subsections in detail.

A. Piezoelectric transducer

A piezoelectric transducer is used to convert the ambient vibration and kinetic energy into electrical energy as shown in Fig. 2. Under mechanical stress, it generates an electric field with alternating polarity [11]. The harvesting AC voltage is rectified using a bridge rectifier and is used to charge a capacitor. The energy stored in the capacitor is used to power a load as shown in Fig. 2. The harvested energy from the piezoelectric transducer depends upon many factors including the resonance frequency, amplitude and frequency of vibration. The resonance frequency is an intrinsic property of the piezoelectric transducer, depending on its geometry, manufacturing parameters and material properties. Using a tip mass, it can be tuned according to specific application requirements. However, this requires human intervention each time while there is a change in vibration characteristic. The amount of energy harvested from a piezoelectric transducer also depends upon the type of application in which the transducer is being employed. The resulting dynamics change the optimum operating point of the transducer in terms of mechanical tuning as well as electrical loading. Therefore, there is a potential to devise a method that harvest maximum energy under given vibration characteristics without human intervention (i.e., without replacing piezoelectric transducers and/or tuning the resonance frequency). Accordingly, we explore the impact of these uncontrollable parameters (vibration amplitude as well as frequency) on the harvested energy using different energy harvesting hardware designs. We also employ the MPP of the transducer to harvested higher energy, as described in the following subsections and find the best design under a given nature of vibration characteristics.

B. Energy harvesting circuits using KEH transducer

In batteryless IoT devices, the load is turned on when the capacitor voltage reaches a turn-on threshold V_{on} and is turned off when the capacitor voltage drops below a turn-off threshold
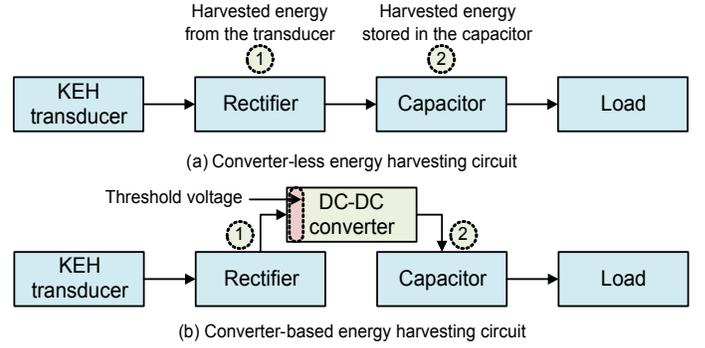

Fig. 5: Illustration of KEH hardware prototypes (a) Converter-less and (b) Converter-based designs

V_{off} as shown in Fig. 3. The stored energy in the capacitor E_{cap} is calculated as:

$$E_{cap} = \frac{1}{2}CV^2 \quad (1)$$

where, C is the capacitance and V is the capacitor voltage. Fig. 3 shows the typical intermittent execution pattern of a batteryless device. The energy consumed by the load E_{load} during its operation is given as:

$$E_{load} = \frac{1}{2}C(V_{on}^2 - V_{off}^2) \quad (2)$$

As Fig. 3 depicts, the frequency of executing the load depends on the rate of charging of the capacitor. There are two main design options for charging the capacitor which are described in detail below.

Converter-less design. In the conventional, converter-less design, the capacitor is placed in parallel to the rectifier. Therefore, the voltage across the transducer is given as:

$$v_{AC} = v_{cap} + 2 \cdot v_d \quad (3)$$

where, v_{cap} is the capacitor voltage and v_d is the voltage drop across the corresponding diode in the full wave rectifier. If the open circuit voltage is higher than the voltage on the capacitor, v_d is approximately constant (one diode drop, typically $350\,\mathrm{mV}$[1]) and thus, the voltage across the transducer equals the capacitor voltage plus two diode drops. This may result in low energy yield. For example, if the capacitor voltage is $3\,\mathrm{V}$ and the input vibration is low, then the open circuit voltage of the transducer may be less than $3\,\mathrm{V}+2v_d$. In this case, no current can flow and thus energy that could have potentially been harvested is wasted. The dependence between capacitor voltage and transducer voltage thus has important implications for the harvested energy.

Converter-based design. In a converter-based design, a DC-DC boost-converter [10] is placed between the rectifier and the capacitor. This allows to optimize the operating point (i.e., harvesting voltage) of the transducer independent of the voltage on the capacitor. For example, the converter can be configured to regulate the transducer voltage at its input to
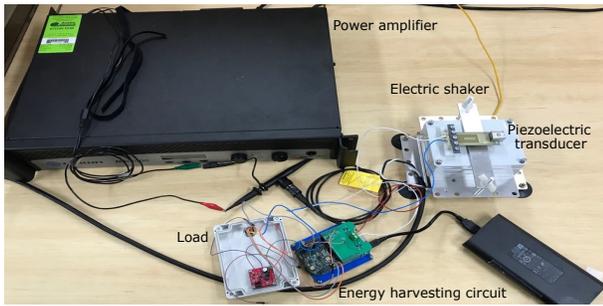
[1]Using schottky diodes

Fig. 6: Experimental setup for measuring the harvested power using KEH converter-less and converter-based hardware designs with a stable load shaker
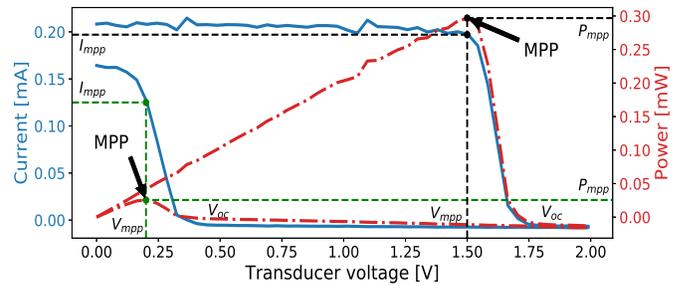

Fig. 7: The Current-Voltage Characteristic Curve (IV), corresponding power and MPP of the piezoelectric transducer operating at the resonance frequency

300 mV by dynamically controlling the current flow from the transducer. This allows to extract energy from the transducer for charging the capacitor even under very low motion or vibrations. It can also be used to fix the transducer voltage to its MPP, extracting higher energy from the transducer. The decoupling of the transducer from the capacitor and load has a significant impact on the current flow from the transducer. Fig. 4 shows the harvesting current from converter-less and converter based designs under same vibration characteristics. In the converter-based design, the capacitor is decoupled from the transducer using a DC-DC converter.

IV. PROTOTYPING AND EXPERIMENTAL SETUP

For our study, we design two KEH hardware prototypes for collecting data from two types of energy harvesting circuits: converter-less (Fig. 5a) and converter-based (Fig. 5b). We use an S230-J1FR-1808XB two-layered piezoelectric bending transducer from MIDÉ technology[2] with a block tip mass of $24.62\,\mathrm{g} \pm 0.5\%$ resulting in a resonance frequency of $25\,\mathrm{Hz}$. All signals are sampled at a frequency of $100\,\mathrm{Hz}$ using an 18-bit ADC. Both designs in Fig. 5 use a $220\,\mu\mathrm{F}$ capacitor to temporarily store the harvested energy and an intermittently powered load[3] consisting of two LEDs, mimicking the behaviour of a batteryless device. The converter-based design (in Fig. 5b) uses an ultra low power TI BQ25504 DC-DC boost converter to step up the transducer voltage. The input threshold voltage of the converter is linearly swept from $500\,\mathrm{mV}$ to $2900\,\mathrm{mV}$ in $100\,\mathrm{mV}$ steps. The prototypes are based on a portable testbed [12] and designed as dataloggers with a focus on enabling accurate measurements of energy rather than on optimizing the harvesting efficiency.

In order to enable a fair comparison between converter-based and converter-less designs, we use a stable 1-lb load shaker[4] along with a power amplifier[4], DSi 1000, to excite the transducer at varying levels of amplitude and frequency of vibration. An arbitrary waveform generator[5], RIGOL DG4162, is used to provide a single tone sinusoidal signal to the power amplifier which drives the load shaker. The experimental
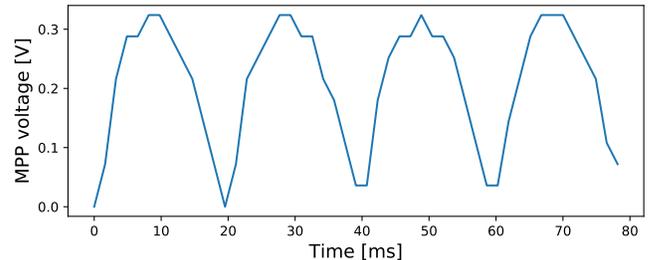

Fig. 8: The MPP voltage changes with the oscillation of the transducer.

setup for measuring the harvested power in converter-less and converter-based designs is shown in Fig. 6. In this experiment, we fixed the signal from the waveform generator to a sine wave with varying amplitude levels (referred as vibration amplitudes in the rest of the paper) from $200\,\mathrm{mV}$ to $1000\,\mathrm{mV}$ peak-to-peak and frequency from $10\,\mathrm{Hz}$ to $50\,\mathrm{Hz}$. These values of vibration amplitude and frequency are selected to reflect the real vibration characteristics from various transport modes [13]. A piezoelectric transducer is mounted on the load shaker, and the converter-less and converter-based energy harvesting circuits are tested consecutively to sample the generated voltage and current signals, using the same transducer.

V. RESULTS AND DISCUSSION

In this section, we present the harvested power from the converter-less and converter-based designs, and study the benefit of operating the KEH transducer at its MPP.

A. MPP of the KEH transducer

In the converter-based energy harvesting circuit, we can choose the input voltage threshold of the DC-DC converter in order to operate the transducer at its MPP. As shown in Fig. 7, the MPP of the piezoelectric transducer is defined by its current-voltage characteristics. We explore the IV characteristics of the piezoelectric transducer to find its MPP using an uncontrolled bridge rectifier and a KEITHLEY 2602B source meter[6]. We rapidly sweep the voltage from zero up to the open circuit voltage and record the corresponding current at a sampling frequency of $15.4\,\mathrm{kHz}$. In order to analyze the MPP

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[2]https://www.mide.com/

[3]In this experiment, we set $V_{on} = 3.38\,\mathrm{V}$ and $V_{off} = 2.18\,\mathrm{V}$

[4]https://controlledvibration.com/product-item/1lb-load-shaker/

[5]https://www.rigolna.com/products/waveform-generators/dg4000/

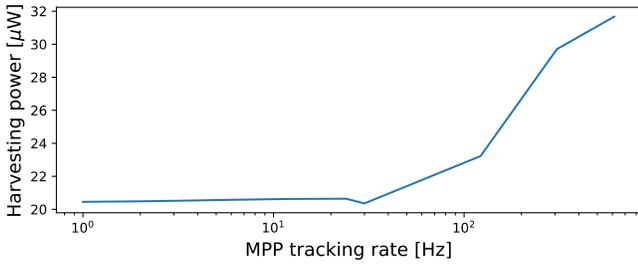[6]https://www.tek.com/keithley-source-measure-units/smu-2600b-series-sourcemeter

Fig. 9: The average transducer power depends on the MPP sampling frequency

Fig. 10: The harvested power in converter-less and converter-based energy harvesting circuits
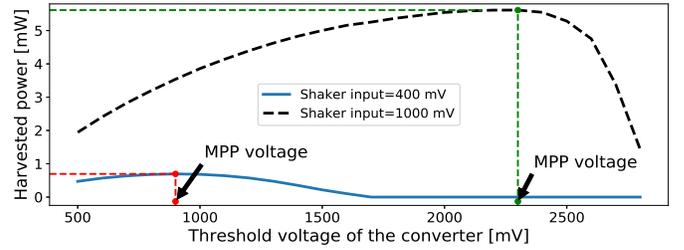

Fig. 11: Adjusting the threshold voltage of converter according to MPP of the transducer allows to harvest higher energy

Recalling, the intermittent execution pattern from Fig. 3, we note that the capacitor voltage is always in the range of turn-on and turn-off thresholds under normal operating conditions. From Eq. 3, we know that the rectified transducer operating voltage equals the capacitor voltage. Thus, without a DC-DC converter, the transducer is operated at voltages between $2.18\,\text{V}$ and $3.38\,\text{V}$ less two diode drops in our prototype. However, Fig. 12 shows that the MPP voltage is often significantly lower. With the converter-less design, the transducer is operated far from the MPP, which can significantly reduce the output power as shown in figure 7. In contrast, by using a DC-DC converter, we can optimize the operating point of the transducer and as a result achieve greatly improved energy yield even with static MPP tracking.

B. Harvested power stored in the capacitor

We employ converter-less and converter-based designs to harvest power at varying levels of input vibrations. Fig. 10 shows the harvested power calculated from the stored energy in the capacitor at varying frequency and amplitude levels of input vibrations. For the converter-based design, we plot the harvested power at the MPP. Fig. 10 shows that both designs harvest highest power at the resonance frequency due to the higher output power from the transducer. At the same vibration amplitude, KEH produces highest power at its resonance frequency. However, the converter-based circuit harvests higher power than the converter-less design at all frequency and amplitude levels of input vibrations. It offers about 26.5 to 409 times (on average, 112 times) higher power than the converter-less design while operating at the resonance frequency under varying vibration amplitudes. The reason for the higher harvested power in the converter-based design is the operation of the piezoelectric transducer at its MPP.

C. Impact of threshold voltage of DC-DC converter on the harvested power

We calculate the harvested power stored in the capacitor in the converter-based design using different voltage thresholds of the DC-DC converter and plot the results in Fig. 11. It shows that at a specific voltage threshold of the DC-DC converter, higher power is harvested. This voltage corresponds to the MPP of the transducer. Fig. 11 also shows that increasing the vibration amplitude (from $400\,\text{mV}$ to $1000\,\text{mV}$) generates a higher transducer voltage, which in turn shifts the dynamic MPP towards a higher average voltage as discussed

of the piezoelectric transducer, we plot two IV curves in Fig. 7. It shows that the current from the transducer decreases with the increase in the output voltage, reaching to zero at the open circuit voltage v_{oc}. Fig. 7 also plots the output power over the transducer voltage. It depicts that the MPP lies near 50-80% of the open circuit voltage. It also shows the corresponding current I_{mpp} and power P_{mpp} at MPP. From the figure, it is clear that with the change in IV curve, the MPP also changes. Fig. 8 shows the dynamic pattern of the MPP voltage over time. The MPP varies with the oscillations of the transducer. We analyse the effect of slow MPP tracking by calculating the power when undersampling the MPP, i.e., we select the harvesting voltage at the MPP and then keep harvesting at that voltage for $1/f_T$ seconds, where f_T is the tracking frequency. Fig. 9 shows that the harvested power significantly increases with increased MPP tracking speed. This means, that in order to extract maximum power from the transducer, we would need to dynamically track its MPP. Practical MPP tracking circuits usually disconnect the harvester and sample the open circuit voltage in order to estimate the MPP. This incurs significant losses while the harvester is disconnected. These losses linearly increase with increasing MPP sampling rate. Furthermore, off-the-shelf DC-DC converters, like the one used in our prototype offer only a fixed MPP sampling interval of $16\,\text{s}$, which is far too low to track the MPP of a KEH transducer. Therefore, the following experiments only consider static MPP tracking, where the MPP is estimated once for the given vibration characteristics and then kept constant.
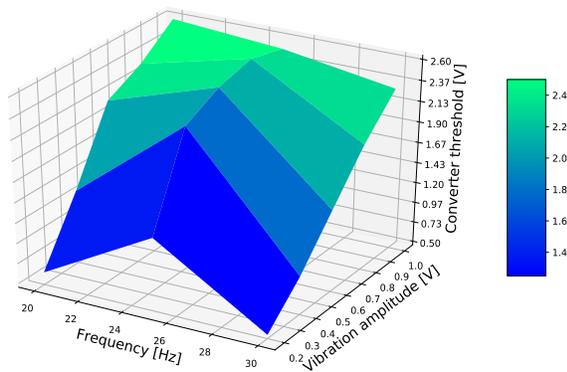
Fig. 12: The threshold voltage of the converter at which maximum power is harvested is a function of the vibration characteristics

in Section V-A. The MPP voltage depends on the underlying vibration characteristics. Fig. 12 plots the voltage threshold of DC-DC converter at MPP with varying vibration frequency and amplitude levels. It shows that the threshold voltage of the converter at which maximum power is attained (i.e., MPP), increases with the increase of the vibration amplitude. For a given vibration level, the MPP threshold is highest at the resonance frequency of the piezoelectric transducer due to the higher transducer voltage at this specific frequency.

D. Power consumption of DC-DC converter

In the converter-less design, the rectifier is the only significant source of losses. The actual charging of the capacitor is almost lossless. In the converter-based design instead, the converter itself causes significant losses and adds overhead in terms of energy, cost and board space. Even if the converter is not operational, for example, when there is no vibration exciting the transducer, it still consumes a so-called quiescent current. The ultra low power DC-DC boost converter[7] TI BQ25504 that we use in our prototype, consumes a maximum of $4.2\,\mu$W of power at a typical capacitor voltage of $3\,$V. This is in the same range as the sleeping current of state of the art microcontrollers. While the converter is actively charging the capacitor, it consumes additional power that, together with various switching losses reduces the efficiency, i.e. the ratio of output power to input power The datasheet shows that the efficiency of the converter generally increases with the increase in input voltage and input current from the transducer. For example, at typical harvesting conditions of $1\,$V and $100\,\mu$A, the converter reaches at an efficiency of more than $80\,\%$.

Despite these losses, we find that the gain from operating the transducer at the MPP by far outweighs the losses incurred by the DC-DC converter.

VI. CONCLUSION AND FUTURE WORK

KEH converts the ambient vibration, motion and mechanical energy into electrical energy to power IoT sensor nodes. The conventional energy harvesting circuit employs a rectifier which rectifies the harvesting voltage to charge a capacitor

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[7]http://www.ti.com/lit/ds/symlink/bq25504.pdf

which is further used to drive a load. However, in this configuration, the transducer is not operated at its MPP which results in lower harvested energy. In this paper, we explore the MPP of the KEH transducer for *optimal* energy harvesting. We statically fix the voltage from the transducer to its MPP resulting in higher harvested energy. We experimentally analyze the dynamic IV characteristics and based on that specify the relation between the MPP tracking frequency and harvesting efficiency, outlining the need for real, dynamic MPP tracking which is not currently available on commercial off-the-shelf hardware. We study the performance of converter-less and converter-based energy harvesting circuits in a controlled environment using a load shaker. The results reveal that, due to operation at MPP, the converter-based circuit harvests, on average, at least one order of magnitude higher power, than the converter-less design, under a wide set of conditions typically found in human-centric applications.

In the future, we intend to study the optimal MPP tracking frequency of KEH transducer as well as the performance of converter-less and converter-based energy harvesting circuits in a real world scenario. In addition, the result of this work outlines the required design for an energy-efficient circuit that solely operates on the harvested energy, resulting in ENO of the batteryless IoT sensor node.

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