A Self-Sensing Synchronized-Switch Circuit for Multi-Input Piezoelectric Energy Harvesting

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***Abstract*—Multi-input piezoelectric energy harvesting (PEH) is promising for battery-free IoT by enhancing power density and bandwidth. However, existing interface circuits face a critical limitation: the inability to effectively manage asynchronous inputs while simultaneously sensing dynamic vibration characteristics without power-hungry external sensors. To address this challenge, a novel multi-input and self-sensing synchronous electric charge extraction (MISS-SECE) interface circuit is proposed. Adopting a shared-inductor architecture to minimize circuit volume, this design leverages a time-based voltage quantization technique. It autonomously extracts full-cycle real-time frequency information by measuring the freewheeling duration, eliminating the need for analog-to-digital converters (ADCs). This self-sensed data is then utilized to trigger switching actions at precise voltage peaks, maximizing energy extraction. Validated through experiments with two piezoelectric transducers, the proposed circuit achieves a 59.79% improvement in harvested power output compared to a multi-input standard energy harvesting (MI-SEH) circuit. This work demonstrates that integrating low-power self-sensing capabilities offers a robust solution for optimizing asynchronous multi-input PEH systems.**

***Index Terms*—Interface circuit, multi-input, piezoelectric energy harvesting (PEH), self-sensing, synchronous electric charge extraction (SECE)**

I. Introduction

Energy harvesting (EH) enables energy-autonomous Internet of Things (IoT) nodes by eliminating battery maintenance [1], [2]. This is particularly critical in inaccessible environments, such as industrial motor fault diagnosis [3] and structural health monitoring [4], [5], where replacing batteries is costly and impractical. Among various sources, Piezoelectric transducers (PTs) are widely used to convert ambient vibration into electricity due to their high power density. Since PTs generate alternating current, an interface circuit with rectification is essential [6]. The standard energy harvesting (SEH) circuit is the most common topology but suffers from low efficiency. To overcome this, synchronized switch interfaces have been developed, primarily categorized into synchronized switch harvesting on inductor (SSHI) [7] and synchronous electric charge extraction (SECE) [8]. Unlike SSHI, SECE offers load independence, making it more robust against environmental variations. The key to these circuits lies in triggering switching actions at precise instants to extract charge. This mechanism effectively minimizes reactive power and maximizes energy conversion efficiency [9].

To overcome the power limitations of single-source systems, multi-input PEH has emerged as a research hotspot.

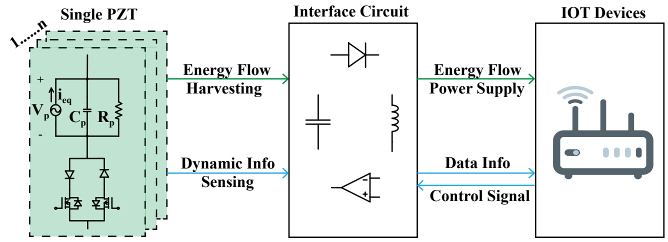

Fig. 1. The block diagram of multiple piezoelectric energy harvesting system.

By harvesting from multiple PTs, these systems significantly enhance total output power and frequency bandwidth [10], [11]. To minimize circuit volume and cost, shared-inductor architectures are widely preferred over stacking multiple independent interfaces. For instance, Romani et al. [12] proposed a synchronous shared-inductor system, while Meng et al. [13] designed a multi-input application specific integrated circuit (ASIC). More recently, advanced time-division multiplexing and asynchronous control strategies have been investigated to further optimize power extraction from distributed sources [14]. However, a critical dilemma remains in these designs: the trade-off between integration and sensing functionality. Although vibration data (e.g., frequency and amplitude) is vital for the aforementioned monitoring applications [15], most existing multi-input circuits focus solely on energy throughput. Conventional solutions typically require separate sensor interfaces and ADCs parallel to the harvester [16]. This approach inevitably increases the system form factor and consumes a portion of the precious harvested energy, contradicting the goal of low-power IoT.

To address the sensing limitation, this paper proposes a multi-input and self-sensing SECE (MISS-SECE) interface circuit. Exploiting the characteristic that SECE remains open-circuit for most of the vibration cycle, the proposed circuit implements a fixed-interval sampling strategy to monitor the piezoelectric voltage. Specifically, a novel quantization technique is developed to digitize the voltage magnitude by recording the duration of a freewheeling signal against a voltage reference. Based on this real-time sensing, the circuit identifies the exact voltage peak to trigger the switching action, thereby extracting maximum energy. As shown in Fig. 1,

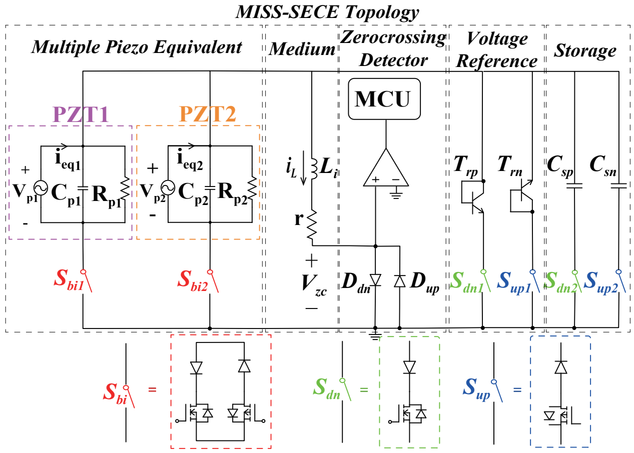

Fig. 2. Circuit topology of MISS-SECE.

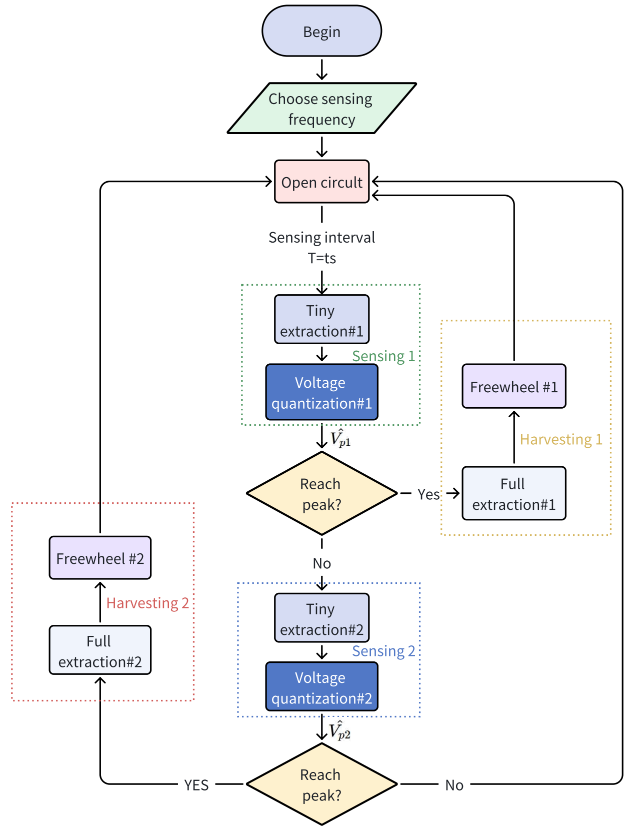

Fig. 3. Control logic flowchart of the proposed MISS-SECE.

the MISS-SECE achieves a dual purpose: providing power to IoT nodes while simultaneously transmitting high-fidelity motion information. The main contributions of this paper are summarized as follows:

- **MISS-SECE Topology:** A novel multi-input interface is proposed to effectively manage asynchronous inputs from multiple PTs. It overcomes the limitations of existing circuits in handling dynamic vibration sources.
- **Self-Sensing Technique:** A voltage quantization technique is developed to autonomously extract full-cycle motion information (e.g., vibration frequency). This eliminates the need for external sensors and reduces system complexity.
- **Enhanced Performance:** A closed-loop control strategy utilizes the sensed data to precisely synchronize switching actions. Experimental results demonstrate a 59.79% improvement in harvested power compared to the multi-input SEH (MI-SEH) circuit.

II. Principle

A. Circuit Topology

To achieve real-time multiple piezoelectric sensing and high-efficiency energy harvesting, the proposed MISS-SECE system is illustrated in Fig. 2. It is compatible with the SS-BECC circuit proposed by the authors' research group [17]. Benefiting from the inherent scalability of the buck-boost-derived topology, the input stage can be readily expanded to accommodate multiple PT channels. Unlike conventional designs that stack independent interfaces, this architecture adopts a shared-inductor topology to minimize component count and volume. The circuit can be functionally decomposed into five key stages.

1) Piezoelectric Input Stage: This stage interfaces with multiple piezoelectric transducers (PTs). Each PT is connected to the harvesting circuit, serving as an AC current source with internal capacitance.

2) Shared Inductor Branch: A single inductor L is employed as the intermediate energy transfer medium. It forms an LC resonant loop with the PT's internal capacitance to perform the synchronous charge extraction.

3) Zero-Crossing Detection (ZCD) Module: Unlike peak detectors, this module specifically monitors the zero-crossing point of the inductor current (I_L). It serves a crucial dual role: during the sensing phase, it determines the termination of the freewheeling interval, providing the necessary timing signal for voltage quantization; during the harvesting phase, it ensures the switches turn off exactly when the current drops to zero, thereby maximizing energy transfer to the storage branch and preventing reverse current flow.

4) Voltage Reference: This block provides stable reference voltages (positive and negative). These references are crucial for the proposed time-based quantization technique to measure the voltage amplitude.

5) Dual-Polarity Energy Storage: To accommodate the AC nature of the source and the control logic, the output stage consists of positive and negative capacitor channels. These channels store the extracted energy and supply the load.

B. Control Logic Implementation

To effectively manage asynchronous inputs using a single shared inductor, a sequential monitoring strategy is imple-

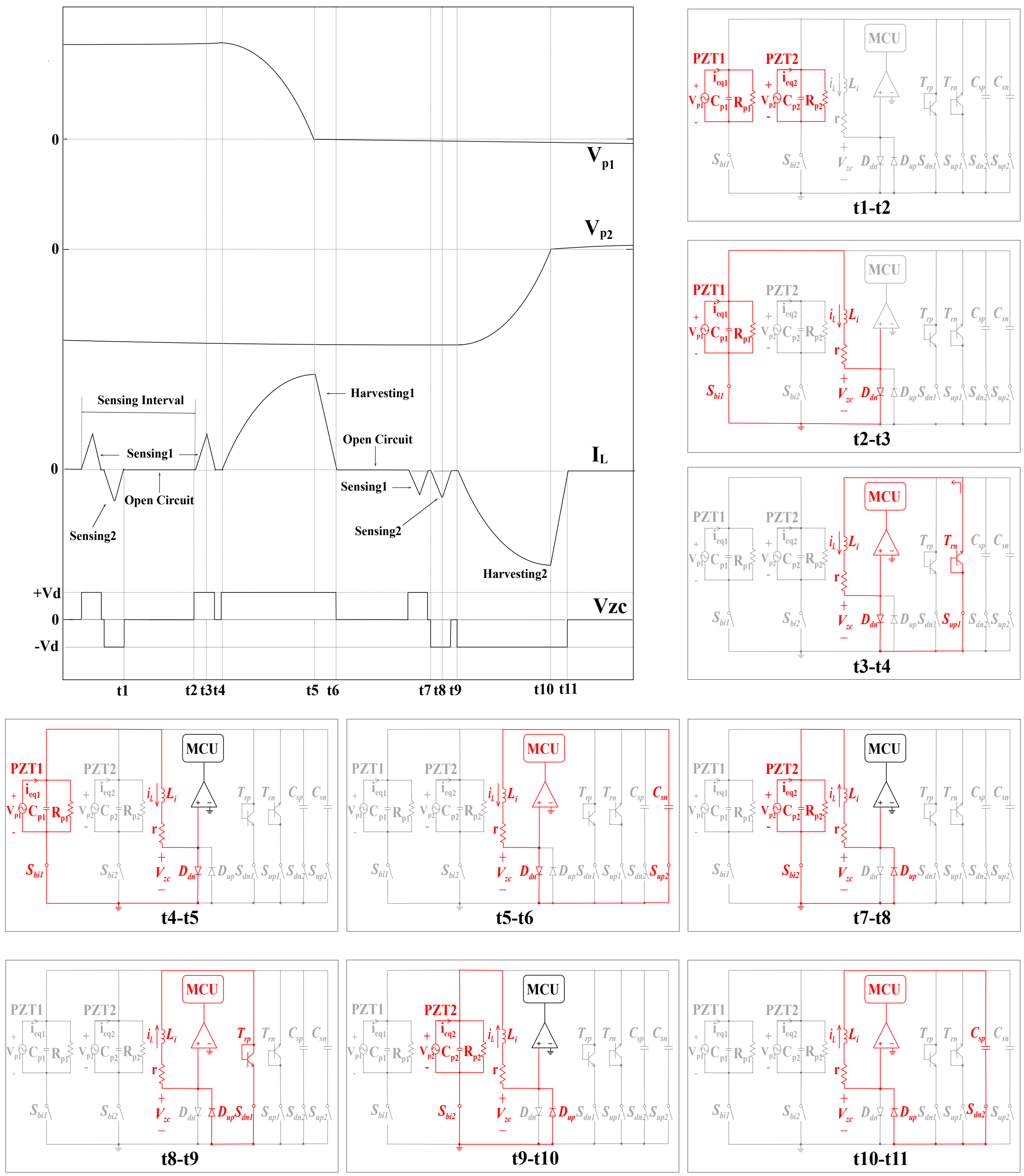

Fig. 4. Conceptual waveform and operation phases.

mented to prevent resource conflicts. The specific control logic is modeled as a finite state machine (FSM), as illustrated in Fig. 3. The system defaults to an open circuit state, where all switches are disabled to minimize static power consumption and allow charge accumulation. A global timer triggers a sensing interrupt at fixed intervals ($T = t_s$), initiating the time-division multiplexing cycle. This mechanism ensures that only one channel accesses the shared energy extraction branch at any given instant.

Upon triggering, the controller first prioritizes channel #1 by executing a tiny extraction to sample its voltage against the reference. If a voltage peak is detected, the system immediately transitions to the harvesting phase, performing a full extraction followed by a freewheel period before returning to

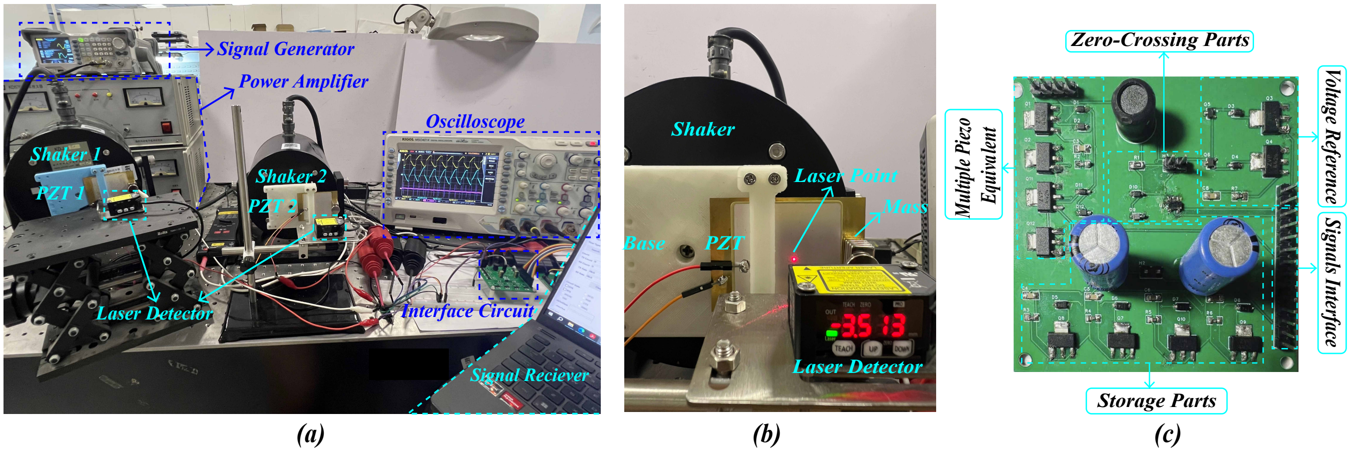

Fig. 5. Experiment setup. (a) Overview. (b) PT Structure. (c) PCB Prototype.

the idle state. Conversely, if no peak is detected in channel #1, the controller bypasses its harvesting stage and immediately proceeds to sense channel #2. A similar peak detection logic is applied to the second channel. If channel #2 reaches its peak, energy is harvested; otherwise, the system returns to the open circuit state to await the next timer cycle. This cascaded check mechanism effectively prioritizes energy extraction while ensuring robust operation without inductor saturation or timing collisions.

C. Working Principle

The detailed operation waveforms and equivalent circuits are depicted in Fig. 4. The proposed MISS-SECE operates in a specific sequence to achieve simultaneous sensing and harvesting. Taking a positive half-cycle as an example, the operation is divided into five distinct phases.

1) Open Circuit: Initially, all switches are off. The piezoelectric current (I_p) charges the internal capacitance (C_p), causing the piezoelectric voltage (V_p) to rise. This phase occupies the majority of the vibration cycle.

2) Sampling Extraction: To monitor the voltage magnitude without depleting the harvested energy, a brief sampling action is initiated at fixed intervals. The switch is turned on for a short, constant duration, extracting a negligible amount of charge into the shared inductor L.

3) Sensing Freewheeling (Quantization): The switch turns off, and the inductor current freewheels against a known reference voltage (V_r). The ZCD module records the duration of this freewheeling sensing period, denoted as t_{fs}. Based on the volt-second balance principle applied to the inductor, the estimated piezoelectric voltage $\hat{v}_p$ can be derived as:

$$\hat{v}_p = \frac{t_{fs}}{t_{cs}}(V_r + 2V_d) + 2V_d \qquad (1)$$

where t_{cs} represents the fixed charging sampling time, and V_d denotes the forward voltage drop of the diodes in the rectification path. Since V_r, t_{cs}, and V_d are constant system parameters, the measured time t_{fs} is strictly linearly proportional to the instantaneous voltage $\hat{v}_p$. This relationship enables the controller to precisely quantify the voltage magnitude in the time domain without using ADCs.

4) Full Charge Extraction (Harvesting): When the system detects the peak of V_p based on the sensed data, the main harvesting sequence begins. The switch closes until V_p drops to zero, transferring the maximum stored energy from C_p to the inductor L.

5) Energy Harvesting Freewheeling: Finally, the switch opens, and the energy stored in L is released to the storage capacitor via the freewheeling diode. The ZCD ensures the switch remains off once the inductor current falls to zero, completing the cycle.

The circuit operates symmetrically for the negative half-cycle by activating the corresponding switches and negative reference path.

III. Experiment

A. Setup

To validate the feasibility and performance of the proposed MISS-SECE, a discrete component prototype was built and tested. The complete experimental setup is illustrated in Fig. 5. The circuit is implemented on a PCB prototype as shown in Fig. 5(c). The switching and quantization logic are realized using a RISC-V microcontroller (CH32V208) running at 144 MHz. To ensure efficient energy transfer, a 100 mH inductor is selected for the shared resonant branch. The output stage employs 22 μF capacitors to store the harvested energy. As shown in Fig. 5(a), the vibration excitation is provided by an electrodynamic shaker.

Two PZT piezoelectric patches are used as asynchronous energy sources. Their key parameters are summarized in Table I.

B. Waveform

Fig. 6 depicts the measured steady-state experimental waveforms of the MISS-SECE system. As shown in Fig. 6(a), the

TABLE I
COMPONENTS OF THE EXPERIMENTAL SETUP

Component	**Model / Specification**
Piezo-patch (PT)	PZT ($70 \times 50 \times 0.6$ mm^3)
Microcontroller	CH32V208 (RISC-V)
Comparator	TLV3201
NMOS	ZVN4424GTA
PMOS	ZVP4424GTA
Bipolar Transistor	2SC4083T106N
Diode (Rectifier)	NSR0240H
Diode (Signal)	1N4148W
Shared Inductor	RLB1014-104KL (100 mH)
Storage Capacitor	ERJ1KM220E12OT (22 μF)
Sampling Resistor	0603WAF2000T5E (200 Ω)

system successfully accommodates the asynchronous inputs from PT1 (28 Hz) and PT2 (18 Hz). Despite the frequency mismatch, independent voltage flipping and energy extraction are observed for each channel, validating the effectiveness of the shared-inductor architecture. Fig. 6 (b) and (c) provide zoomed-in views of the synchronized switching instants. It can be clearly observed that the extraction process is triggered exactly at the voltage peaks. Upon switching, the piezoelectric voltage (V_p) drops instantly to zero. This rapid discharge confirms that the internal charge on C_p is fully transferred to the inductor without significant residual voltage. Furthermore, the absence of voltage undershoot or oscillation validates the precision of the ZCD module in preventing reverse current flow.

C. Results

Fig. 7 visualizes the real-time voltage quantization results for the two piezoelectric transducers. Since the inputs are asynchronous (28 Hz for PT1 and 18 Hz for PT2), the circuit independently samples and reconstructs their respective voltage envelopes. The discrete data points in the figure correspond to the freewheel durations recorded by the microcontroller. It is evident that the quantized values closely track the sinusoidal variations of the actual piezoelectric voltage. This high-fidelity reconstruction validates that the proposed time-based quantization technique effectively captures the motion information (frequency and phase) without requiring ADCs module. Based on this accurate sensing, the controller successfully identifies the optimal switching instants (voltage peaks) for each channel.

To evaluate the energy harvesting performance, Fig. 8 compares the measured harvested power of the proposed MISS-SECE against the MI-SEH circuit and individual SEH circuits. The benchmark MI-SEH circuit consists of two independent full-bridge rectifiers connected in parallel to a single storage capacitor. The maximum output power of the MISS-SECE reaches 347.00 μW, whereas the MI-SEH saturates at 217.16 μW. This represents a 59.79% increase in power extraction capability, which is attributed to the synchronized switching mechanism that eliminates charge waste on the internal capacitance. Furthermore, the proposed circuit demonstrates robust load independence. As shown by the blue curve in Fig. 8, the

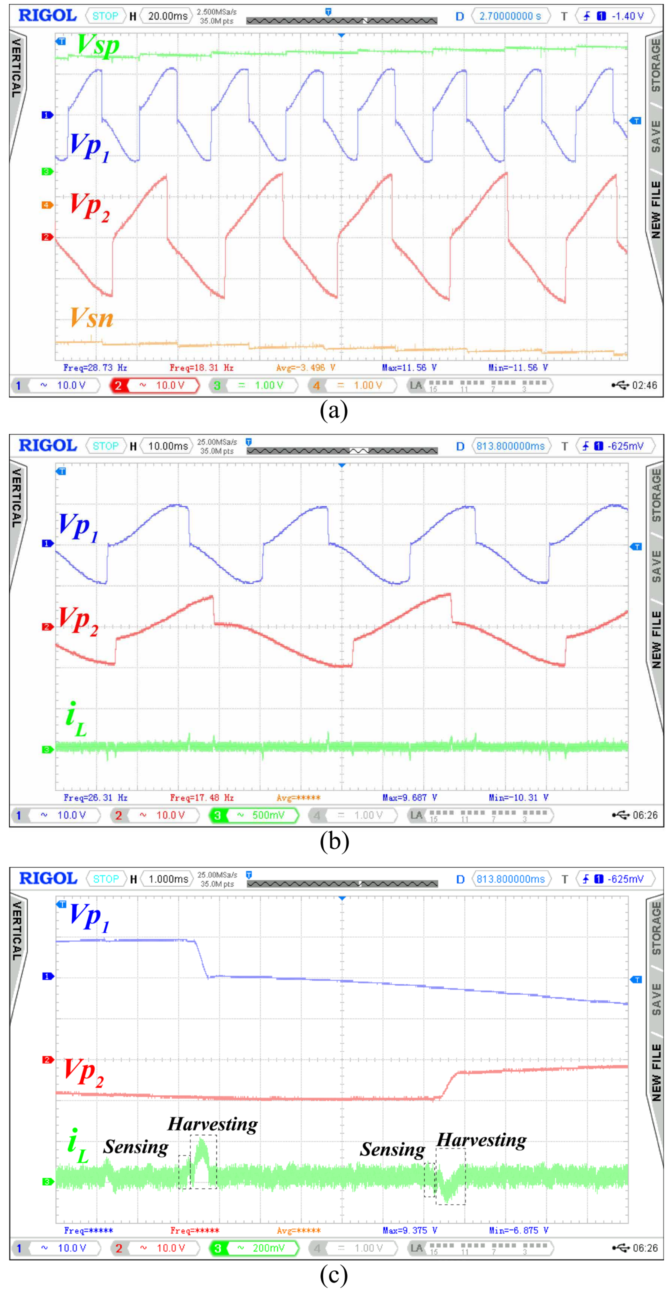

Fig. 6. Experiment waveform. (a) Overview. (b) Waveform of Synchronized Instant. (c) Enlarged View.

output power of the MISS-SECE increases with the output voltage and maintains a high level without dropping off. In sharp contrast, the MI-SEH and individual SEH circuits exhibit a strong dependence on load voltage, with power dropping significantly after reaching a peak. This characteristic makes the MISS-SECE particularly suitable for charging storage elements to higher voltage without efficiency degradation.

IV. CONCLUSION

This paper presents a novel multi-input and self-sensing SECE (MISS-SECE) interface circuit designed to tackle the

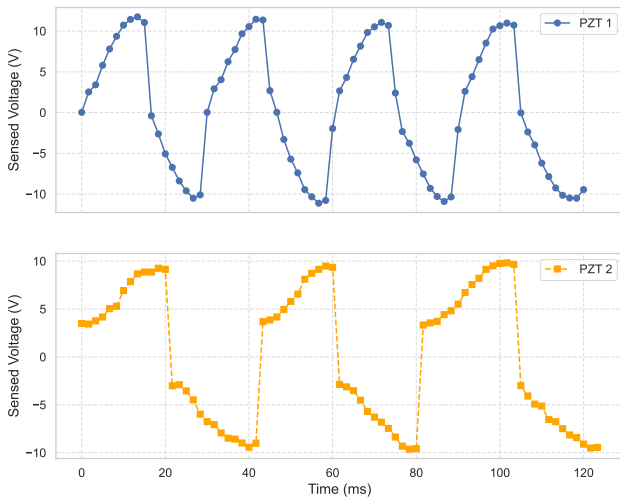

Fig. 7. Sensed results.

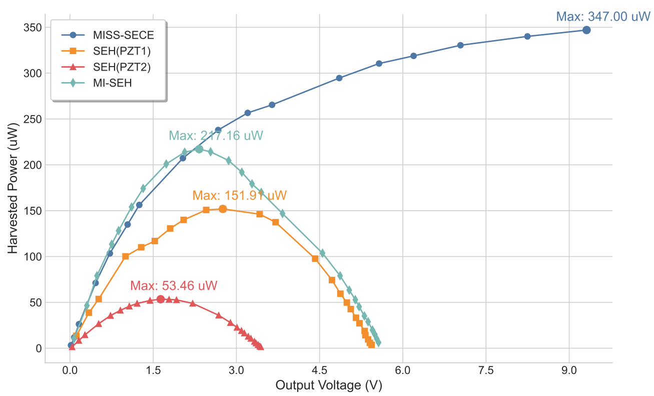

Fig. 8. Harvested power.

dual challenges of efficient energy extraction and intelligent motion sensing in distributed IoT applications. By leveraging a shared-inductor architecture and a time-based voltage quantization technique, the proposed system autonomously captures real-time vibration characteristics from asynchronous sources without relying on analog-to-digital converters. This integration of sensing capability allows for precise closed-loop control, which addresses the timing inaccuracies often found in conventional multi-input circuits. Experimental validation confirms that the self-sensing mechanism enables robust phase synchronization, resulting in a 59.79% increase in harvested power compared to the standard multi-input standard energy harvesting (MI-SEH) benchmark while maintaining load independence. While the current discrete prototype validates the proposed methodology, future work will focus on minimizing the power overhead of the control logic and integrating a cold-start mechanism. These advancements aim to eliminate the dependency on auxiliary power supplies, thereby achieving a fully self-powered system with maximized end-to-end efficiency.

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