A 416 nW Buck-Converter with Dynamically-Configured and Adaptively-Controlled Direct MPPT for Triboelectric Energy Harvesting with 88% Peak Efficiency

Seneke Chamith Chandrarathna, and Jong-Wook Lee

School of Electronics and Information, Kyung Hee University, jwlee@khu.ac.kr

Kyung Hee University
WINS Laboratory

I. INTRODUCTION

This paper presents a dynamically configured, high-voltage and ultra-low-power (ULP) DC-DC converter for triboelectric energy harvesting. The proposed converter IC, fabricated in a 180 nm high-voltage (HV) Bipolar-CMOS-DMOS(BCD) process, achieves input 48V/output (5V) conversion with an adaptively-controlled direct maximum power point tracking (ACD-MPPT) algorithm, which continuously tracks the input power by evaluating the input voltage and current. Through the dynamically configured interface circuit (DIC), the MPPT controller handles two triboelectric nanogenerators (TENGs) by optimally selecting either series or parallel configurations. The converter achieves tracking and end-to-end efficiencies of 98% and 88%, respectively, while consuming 416 nW at 5V output.

II. DESCRIPTION

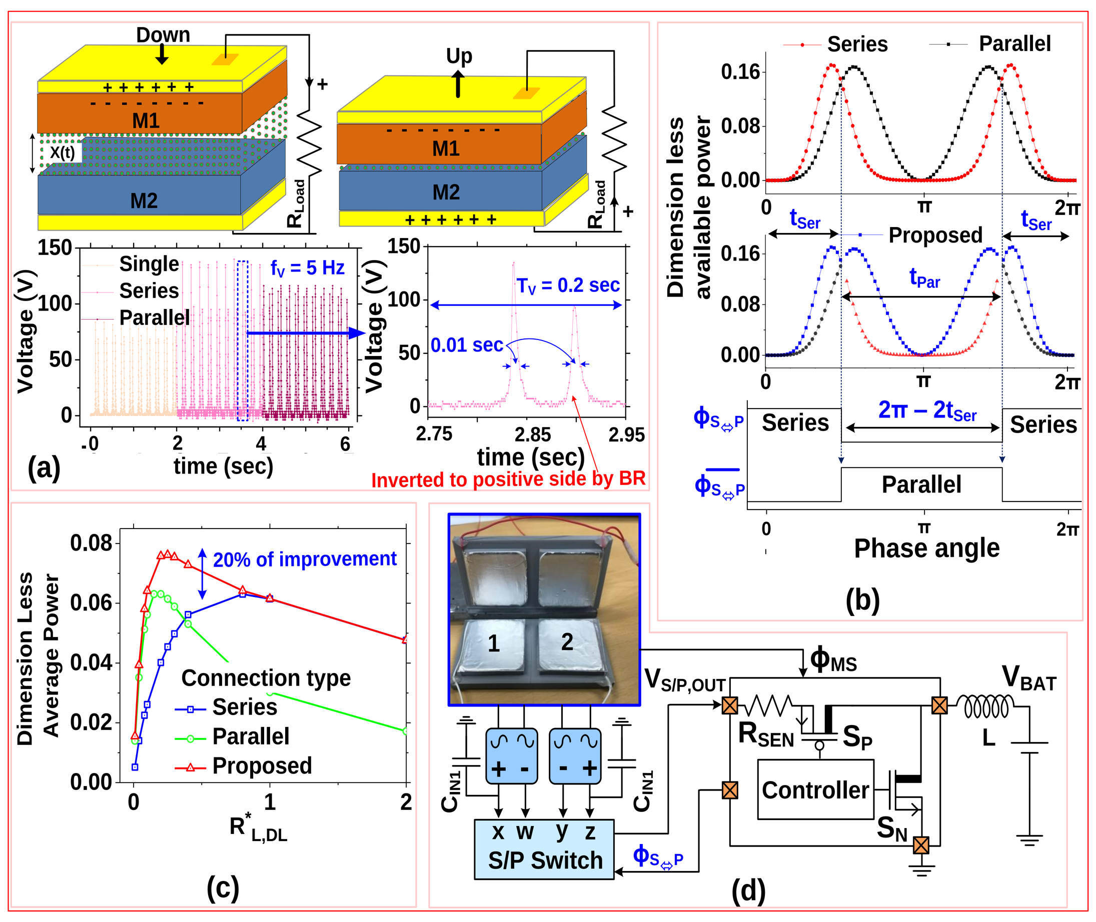

Fig .1. (a) TENG: Schematics and results. (b) Power variation. (c) Average power variation. (c) Simplified circuit.

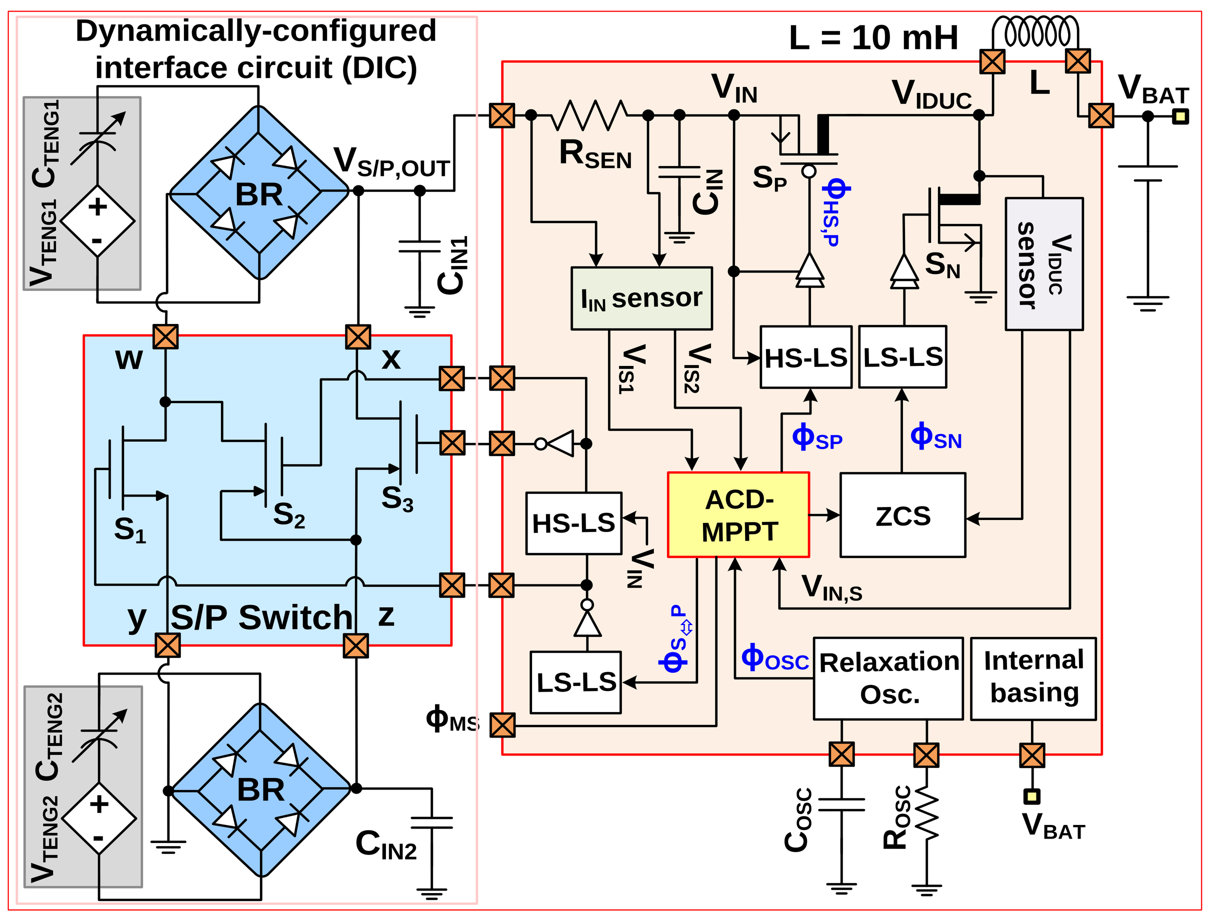

Fig .2. (a) TENG: Schematics and results. (b) Power variation. (c) Average power variation. (c) Simplified circuit.

As shown in the measured results of Fig. 1(a), however, V_{TENG} exists only during short times of 0.02 sec. This corresponds to ~ 10% of the period (T_V ~ 0.2 sec), resulting in a relatively low available power (P_{TENG}) [1]. To harvest P_{TENG}, in this work, we combine multiple TENGs and discuss three design techniques: 1) an effective method to combine multi-TENGs using a dynamically-controlled interface circuit (DIC), which different from [2], 2) an adaptive-controlled tracking algorithm to tackle the variation of P_{TENG}. 3) innovating an ultra-low-power (ULP) and high voltage DC-DC buck converter. Fig. 1(b) shows the dimensionless power variation ($P_{TENG,DL}$) for series and parallel connections, and we propose a method to select those optimally. Fig. 1(c) presents the measured $P_{AVE,DL}$ with R_L, which shows that 20% of increment due to the proposed method. Fig. 1(c) shows the simplified block diagram of the proposed energy harvester with the homemade TENGs.

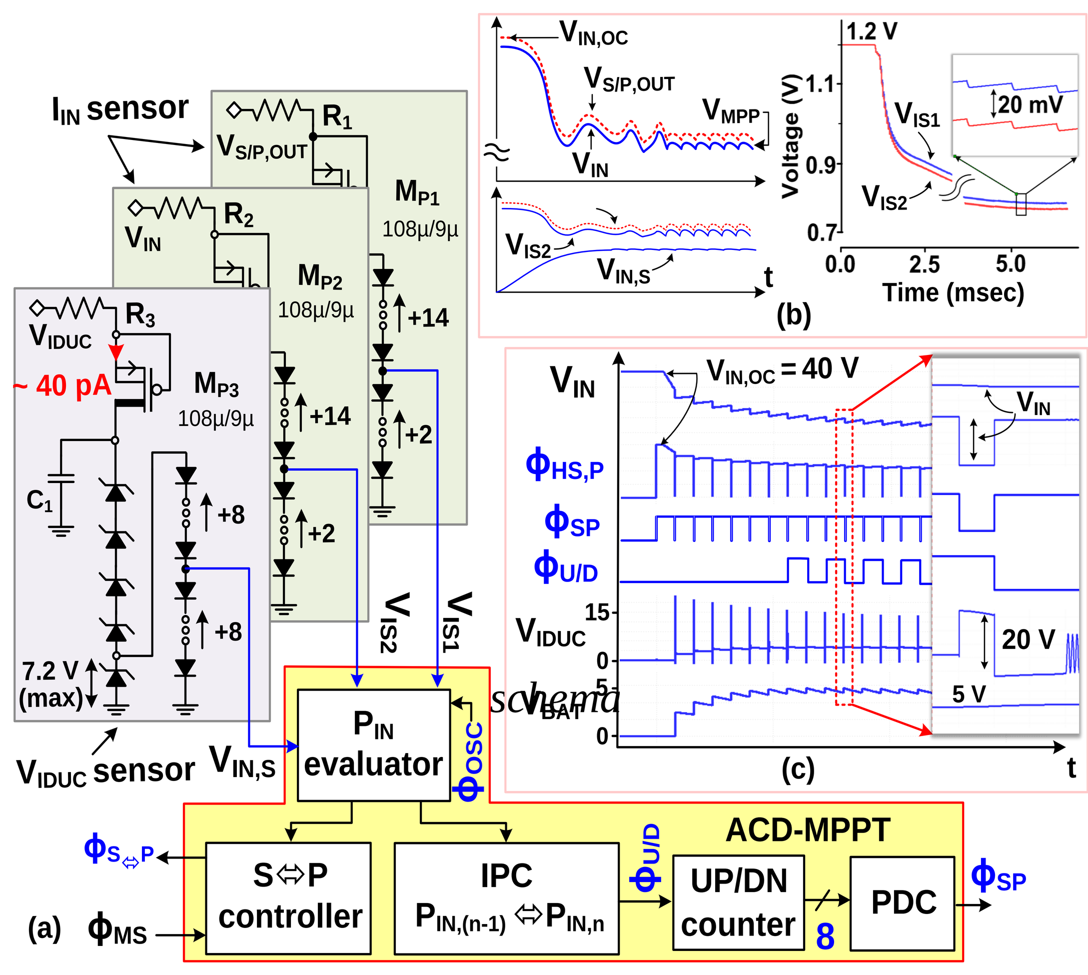

Fig .3. (a) Schematic of I_{IN} and V_{IDUC} sensor and block diagram of ACD-MPPT. (b & c) Related waveforms.

Fig. 2 shows the overall block diagram of the proposed energy harvester, including a ULP DC-DC buck converter, two bridge rectifiers (BRs), and a DIC with two TENGs. The buck converter employs an ADC-MPPT controller that evaluates the input power (P_{IN}) by directly measuring the I_{IN} and V_I. This method provides accuracy than the signal parameter tracking methods [2]. Fig. 3(a) shows the block diagram of ACD-MPPT, including schematics of I_{IN} and V_{IDUC} sensors. Depending on the series or parallel configurations, the DIC generates the output $V_{S/P,OUT}$. The I_{IN} sensor detects the variation of $V_{S/P,OUT}$ and VIN using resistor R_{SEN} (~ 50 kΩ). This is scaled down using diode arrays, and the inputs V_{IS1} and V_{IS2} for ADC-MPPT are generated as shown in Fig. 3(b). Fig. 3(c) shows the typical waveforms of ACD_MPPT when the open-circuit voltage ($V_{IN,OC}$) is 40 V.

III. MEASUREMENT RESULTS

Fig. 4(a) shows the chip photo with an active area of ~ 6 mm^2 c, a fabricated DIC, and the measurement setup. The LED array glows periodically when $V_{S/P,OUT}$ is directly connected to TENGs. The results show that DIC can handle 95 V of peak V_{TENG1} while switching between series and parallel TENG configuration. Fig. 4(b) shows the waveforms of the ACD-MPPT controller when TENG is emulated using $V_{IN,OC}$ = 40 V and RTENG = 80 MΩ that gives PTENG = 5 µW. Fig. 4(c) shows the waveforms of the zero-current-switching controller while regulating the output V_{Bat} = 5 V.

Table. 1. Performance comparison

	[2]	[3]	[4]	[5]	This work
Process (nm)	180 BCD HV	350 BCD	250 BCD	180 BCD HV	180 BCD HV
# of Sources	1	1	1	1†	2
Connection type	Master-slave	-	-	-	Series ⇔ Parallel
Source type	Ideal	Piezo electric	Electro static	Tribo electric	Tribo electric
$V_{S,peak}$††(V)/ V_{IN} (V)	48/48	7/7	60/60	70/70	100/ 48
P_{IN} min	-	33 µW	1 µW	4.5 µW	0.8 µW
V_{OUT}	1 V Regulated	1 – 8 V	1 – 5 V	1 – 5 V	5 V Regulated
Tracking Parameters	I_{OUT}	$V_{IN,OC}$	I_{OUT}	$V_{IN,OC}$	V_{IN}, I_{IN}
Power consumption	-	10 µW	500 nW	-	416 nW
η_{MPPT}	-	99 %	99 %	97 %	98 % @ 74.6 µW of P_{IN}
η_{EE}	-	-	85 %	-	88 % @ 4 MΩ of R_{TENG}
η_{CONV}	85.4%	80 %	-	51.1 %	86.2 %

†Dual inputs using a single TENG ††Peak amplitude of the input source

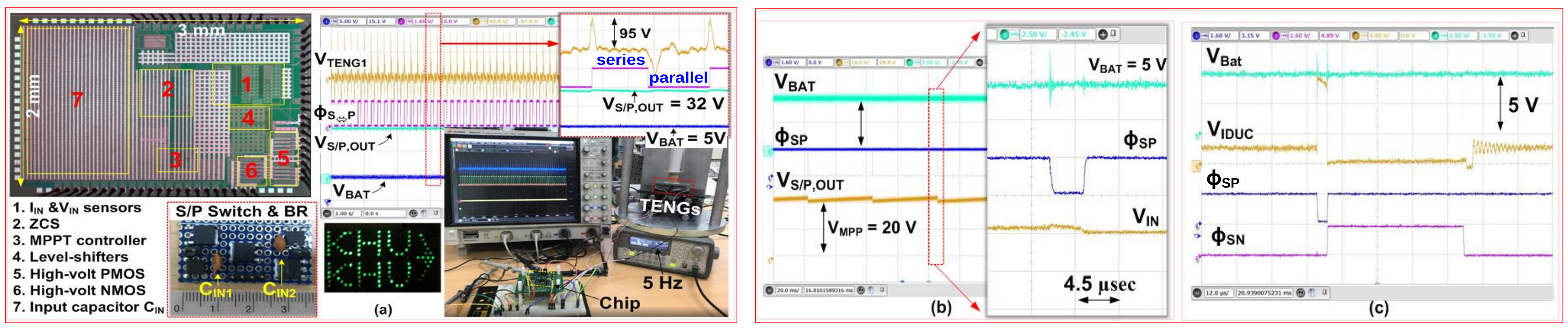

Fig .4. (a) Die photo, the experiment setup including vibrator for THENs, and measured results. Measured waveforms for the operation of (b) MPPT (c) the zero-current-switching controller.

Conclusion

Table. 1 can conclude the performance of this design. We have proposed a method that can optimally select the configuration of the TENGs. The maximum peak voltage of the TENG is 100 V, and the minimum input power is around 0.8 µW, while regulating V_{OUT} at 5 V. The proposed ACD-MPPT can track both V_{IN} and I_{IN} in order to realize the maximum power from TENGs, which is different from others. The power consumption of the system is around 416 nW. The converter achieves tracking and end-to-end efficiencies of 98% and 88%, respectively.

References

[1] J. Peng, et al., Sci. Adv, Dec. 2017.
[2] D. Yan, et al., IEEE Symp. VLSI Circuits, Dig. Tech. Pap. 2019.
[3] Y. Song, C. H. Chan, Y. Zhu, L. Geng, S. P. U and R. P. Martins, “Passive noise
[3] M. Shim, et al., J. Solid-State Circuit, Oct. 2011.
[4] S. Stanzione, et al., ISSCC Dig. Tech. Papers, 2015.
[5] I. Park, et al., ISSCC Dig. Tech. Papers, 2018.

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