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## 30.3 A Bias-Flip Rectifier with a Duty-Cycle-Based MPPT Algorithm for Piezoelectric Energy Harvesting with 98% Peak MPPT Efficiency and 738% Energy-Extraction Enhancement

Xinling Yue, Sundeep Javvaji, Zhong Tang, Kofi A.A. Makinwa, Sijun Du

Delft University of Technology, Delft, The Netherlands

Synchronized bias-flip rectifiers, such as synchronized switch harvesting on inductor (SSHI) rectifiers, are widely used for piezoelectric energy harvesting (PEH) [1], which can replace the use of batteries in many IoT applications, thus reducing both system volume and maintenance cost. However, the output power extracted by such rectifiers strongly depends on the impedance matching between the piezoelectric transducer (PT) and the circuit. To maximize this, two maximum power point tracking (MPPT) algorithms are often used. As shown in Fig. 30.3.1 (left), the Perturb & Observe (P&O) (a.k.a. hill-climbing) algorithm adjusts the rectified output power in a stepwise manner towards the maximum power point (MPP), thus establishing robust and continuous MPPT. However, accurately sensing the rectified output power often requires complex and power-hungry hardware [1, 2]. Another simpler algorithm is based on the fractional open-circuit voltage (FOCV) and involves periodically measuring the PT's open-circuit voltage amplitude ($V_{OC}$) and regulating the rectified voltage ($V_{REC}$) to a level ($V_{MPP}$), which corresponds to the MPP [3–6]. However, the PT must be periodically disconnected from the rectifier to measure $V_{OC}$, resulting in wasted energy, while the inherent delay in sensing $V_{OC}$ variations reduces the overall tracking efficiency. Furthermore, a calibration step is usually necessary to determine $V_{MPP}$, since this depends on the actual PT voltage flip efficiency ($\eta_F$) of the bias-flip rectifier.

In this paper, a duty-cycle-based MPPT algorithm is proposed, which combines the advantages of the P&O and FOCV algorithms while eliminating their drawbacks. As shown in Fig. 30.3.1 (right), when a weakly coupled PT is vibrating at its natural frequency, it can be modelled as an AC current source $I_P$ in parallel with a capacitor $C_P$. The system consists of an SSHI rectifier, a buck-boost DC-DC converter to adjust the $V_{REC}$, and an MPPT controller. While extracting the AC energy from the PT, the rectifier switches periodically between conducting and cut-off modes. It generates a cut-off signal, *CO*, which is "high" when the rectifier is cut-off and "low" when it is conducting (the red waveform). The proposed MPPT algorithm exploits the relationship between the MPPT efficiency ($\eta_{MPPT}$) and the duty-cycle of *CO* ($D_{CO}$). Through mathematical analysis, this work finds that $\eta_{MPPT}=1-\cos^2(\pi D_{CO})$, where $\eta_{MPPT}$ is the ratio of the actual rectified power to the optimal output power at the MPP. As shown in Fig. 30.3.1 (right), operation at the MPP can then be achieved by regulating $D_{CO}$ to 50%, regardless of $V_{OC}$ and $\eta_F$. Furthermore, due to the squared cosine relationship, the algorithm is robust to $D_{CO}$ sensing errors. For example, a $D_{CO}$ error of ±5% (or ±10%) results in $\eta_{MPPT}$ still greater than 97% (or 90%). Compared to the conventional P&O and FOCV, the proposed duty-cycle-based MPPT algorithm has the following advantages: 1) it is independent of $V_{OC}$ or $\eta_F$, so no calibration is required; 2) the PT is always connected to the rectifier, so no energy is wasted; and 3) continuous MPPT is possible. These advantages simplify its circuit implementation, resulting in a prototype PEH dissipating only 307nW in the MPPT controller.

The flowchart of the proposed MPPT algorithm is shown in Fig. 30.3.2 (top). The $D_{CO}$, is sampled in every *CO* period by measuring its ON and OFF pulse widths. If $D_{CO}$<50%, energy harvested by the PT will charge the rectifier output capacitor $C_{REC}$, thus increasing its voltage $V_{REC}$ towards the MPP. If $D_{CO}$ exceeds 50%, this means that $V_{REC}$ exceeds the $V_{MPP}$, so some of the energy in $C_{REC}$ is transferred to the storage capacitor $C_S$ via a DC-DC buck-boost converter in order to maintain $V_{REC}$ around $V_{MPP}$ by regulating $D_{CO}$ to around 50%. At the beginning of the DC-DC transfer, a voltage level $V_{RECS}$, which is slightly lower than the initial $V_{REC}$, is set as the lower threshold of the $V_{REC}$ hysteresis window. Clocked by an on-chip oscillator (OSC), the buck-boost conversion operates for multiple cycles until $V_{REC}<V_{RECS}$. This flow will repeat until next time when $D_{CO}$ exceeds 50%, to achieve MPPT.

The proposed architecture consists of an SSHI rectifier with its own control block, and a buck-boost converter with an MPPT controller (Fig. 30.3.2). The SSHI rectifier consists of an FBR, an active diode and an off-chip inductor $L_M$ shared with the DC-DC converter. When the voltage across the PT ($V_{PT}$) needs to be flipped, the FBR switches from conducting mode to cut-off mode. This causes a *CO* rising edge, which is used to generate an SSHI flipping pulse that briefly connects $L_M$ across the PT, thus initiating a closed RLC loop to flip $V_{PT}$. The *CO* signal is also sent to the MPPT controller, where its duty-cycle $D_{CO}$ is measured. If $D_{CO}$ exceeds 50%, the DC-DC converter is enabled at the next low-*CO* period to transfer some energy from $C_{REC}$ to $C_S$, and thus maintaining $V_{REC}$ around the $V_{MPP}$. A hysteresis window, with a lower threshold $V_{RECS}$ (a fraction of the initial $V_{REC}$), prevents $V_{REC}$ from dropping too much. The upper hysteresis threshold is automatically set to $V_{MPP}$ by the $D_{CO}$=50% condition, and so an explicit voltage threshold is not required. The buck-boost converter is controlled by an on-chip OSC, and uses the shared $L_M$ to transfer energy from $C_{REC}$ to $C_S$. The timing of the switching signal, $S_{PD}$, is controlled by a zero-crossing detector (ZCD).

Figure 30.3.3 shows the MPPT controller. The $D_{CO}$ is sensed by two equal on-chip capacitors, $C_{RGL}$ and $C_{RGR}$. When *CO* is high, $C_{RGL}$ is charged by an on-chip current source to $V_H$; while $C_{RGR}$ is charged to $V_L$ when *CO* is low. To cope with a wide range of PT vibration frequency (half of *CO* frequency), $C_{RGL}$ and $C_{RGR}$ can be adjusted in 8 steps between 5.4pF and 32.2pF. The resulting voltages $V_H$ and $V_L$ are compared to generate the *PO* signal, which indicates the polarity of $D_{CO}$ around the 50% target. When $D_{CO}$>50%, *PO* stays low; otherwise, a pulse is generated. The $C_{RGL}$ and $C_{RGR}$ are reset by a short pulse, $S_{CV}$, at the end of each *CO* period. When *PO* stays low, meaning that $D_{CO}$ exceeds 50% (or $V_{REC}$ exceeds $V_{MPP}$), a DC-DC enable signal, *COM*, is generated to start the DC-DC conversion. The lower hysteresis threshold, $V_{RECS}$, is generated by a switched-capacitor voltage divider. In this design, $V_{RECS}$ can be turned from 97%×$V_{REC}$ to 99.5%×$V_{REC}$ to adjust the ripple of $V_{REC}$ during DC-DC conversion.

The proposed circuit was fabricated in a 0.18μm BCD process and has an active area of 0.47mm$^2$ (Fig. 30.3.7). It is tested with a commercial PT (PEH-S128-H5FR-1107YB) excited at its resonance frequency of 230Hz. Figure 30.3.4 shows the measured waveform. The system starts from the cold state with $V_{OC}$=1.5V and $L_M$=27μH. $V_{REC}$ then increases steadily because $D_{CO}$ is less than 50% and the DC-DC converter is disabled. When $V_{REC}$ reaches $V_{MPP1}$ (~2.47V), $D_{CO}$ is 50%, indicating that the MPP has been reached. The DC-DC converter is then enabled by the MPPT controller to maintain $V_{REC}$ at 2.47V by transferring the harvested energy to $V_S$ during the $MPPT_1$ period. When the vibration excitation is increased to $V_{OC}$=2V, the new $V_{MPP}$ increases and $D_{CO}$ becomes lower than 50%. The proposed circuit can sense the acceleration variation in half cycle and start to converge to the new MPP. As a result, the MPPT block disables the DC-DC converter so that $V_{REC}$ builds up. After $D_{CO}$ reaches 50% again, $V_{REC}$ is maintained at the new MPP (~3.42V) in the $MPPT_2$ period. The MPPT convergence time is mainly affected by the capacitance of $C_{REC}$. The bottom-right plot shows the measured output power versus $V_{REC}$ with the same $V_{OC}$ and $L_M$ as used in the waveform. It shows that the optimal $V_{MPP}$ for 1.5V $V_{OC}$ (or 2V $V_{OC}$) is 2.4V (or 3.3V), which is very close to the regulated $V_{REC}$ of 2.47V (or 3.42V) measured and shown in the waveform. The zoomed-in $V_{REC}$ waveform is also shown in the figure. Each regulation process is done through a number of DC-DC conversion cycles indicated by the pulse signal $S_{PC}$.

The output power of an SSHI rectifier versus the $D_{CO}$ with 1.5V and 2V $V_{OC}$ is shown in Fig. 30.3.5 (top-left). At their peak power points, the optimal duty cycles are 47.58% and 48.52% respectively, which are close to 50%. These results validate the analytical expression of $\eta_{MPPT}$. The shift of optimal $D_{CO}$ from 50% to a slightly lower value is mainly due to the non-zero voltage drop of the active rectifier. However, thanks to the high tolerance to $D_{CO}$ errors of the proposed MPPT algorithm, even when the system regulates $D_{CO}$ to 50% instead of to the actual optimal value, the MPPT efficiency $\eta_{MPPT}$ is maintained above 99%. The measured output power from an FBR and the proposed SSHI rectifier with different inductors (different $\eta_F$) at $V_{OC}$=2V shows that the proposed rectifier achieves a peak output power of 272.5μW, with 738% enhancement compared to an FBR (36.9μW). The MPPT efficiency with different input $V_{OC}$ and $\eta_F$ is also shown in Fig. 30.3.5 (bottom). From these two plots, regardless of $V_{OC}$ and $\eta_F$, the optimal $D_{CO}$ is always around 50%, while the $\eta_{MPPT}$ remains high. The peak $\eta_{MPPT}$ is 98% and the average efficiency is around 96% for a wide range of $V_{OC}$ and $\eta_F$.

Fig. 30.3.6 compares the proposed MPPT design with the state-of-the-art. It occupies a compact area, while enabling continuous MPPT without using an explicit power sensor. It shows no dependency on rectifier parameters: $V_{OC}$ and $\eta_F$. It achieves 98% peak MPPT efficiency and up to 738% power extraction enhancement compared to an FBR.

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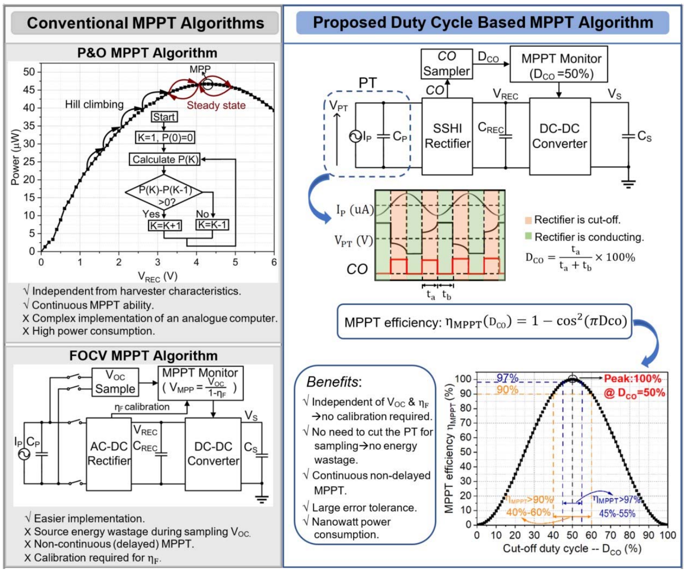


**Figure 30.3.1: Conventional MPPT algorithms (left); simplified architecture, function and its graph of the proposed duty cycle based MPPT algorithm (right).**

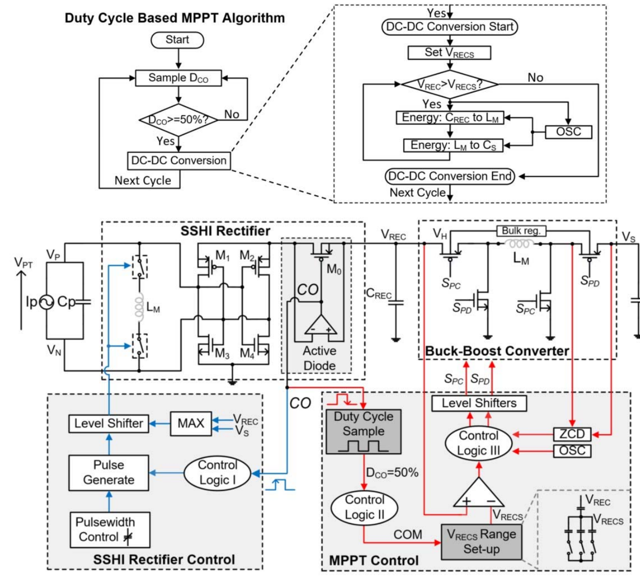


**Figure 30.3.2: Duty cycle based MPPT algorithm and DC-DC working logic flow charts (top); block diagram of the proposed PEH system (bottom).**

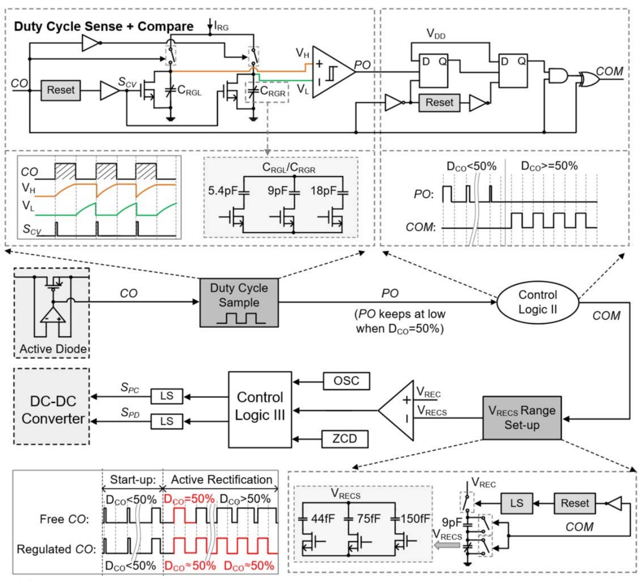


**Figure 30.3.3: Duty cycle sampling block of the proposed system; output waveform of free CO without MPPT and regulated CO with proposed duty cycle controlling.**

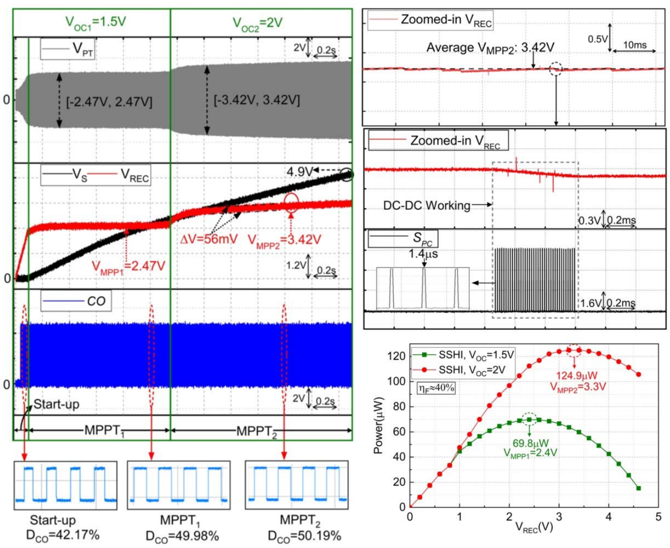


**Figure 30.3.4: Measured waveforms of the MPPT transient time with input 1.5-V $V_{OC}$ and 2-V $V_{OC}$ (left); zoomed-in DC-DC converter working moment (top, right); measured output power of SSHI versus $V_{REC}$ rectifier with 1.5-V and 2-V $V_{OC}$ (bottom, right).**

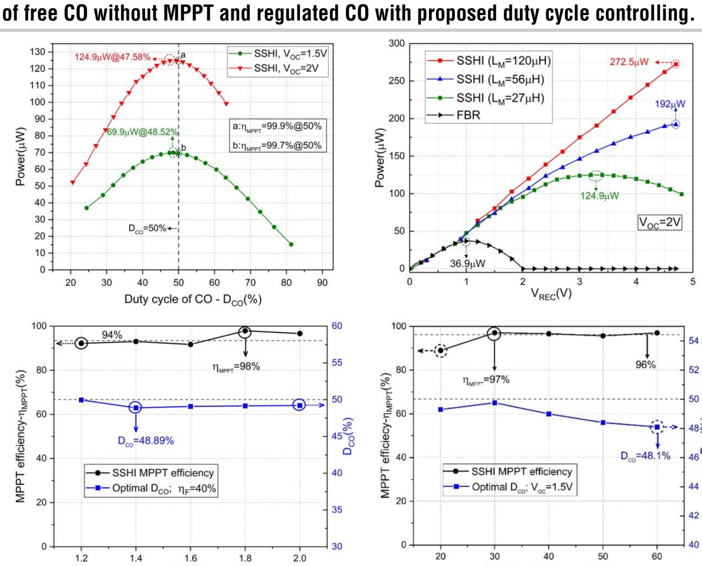


**Figure 30.3.5: The measured output power versus $D_{CO}$ (top, left); measured output power of proposed SSHI rectifier versus $V_{REC}$ (top, right); MPPT efficiency and optimal $D_{CO}$ versus different $V_{OC}$ (bottom, left) and $\eta_F$ (bottom, right).**

| | [3] ISSCC'14 | [4]ISSCC'16 | [5] ISSCC'19 | [1] VLSI'19 | [2] ISSCC'20 | [6] ISSCC'22 | **This work** |
|---|---|---|---|---|---|---|---|
| Technology (μm) | 0.35 | 0.35 | 0.18 | 0.13 | 0.6 | 0.065 | **0.18** |
| Technique | Comparator-based dual mode | P-SSHI | SPFCR | P-SSHI | PSECE | SECE | **SSHI** |
| Harvester Type | PEH-MIDE V21BL | PEH MIDE V21B & V22B | PEH-MIDE PPA1021 | PEH-MIDE PPA1021 &PPA1011 | PEH | TEG/PV/PEH | **PEH-S128-H5FR-1107YB** |
| Piezoelectric Capacitance(nF) | 11 | 26, 20, 9 | 22 | 20 &100 | 24 | 24 | **42** |
| Resonant Frequency(Hz) | 100* | 134.6-229.2 | 200 | 100-180 | 56 | N/R** | **230** |
| MPPT Algorithm | FOCV | FOCV | FOCV | P&O | P&O | FOCV | **Duty Cycle Based** |
| Continuous MPPT | No | No | No | Yes | Yes | No | **Yes** |
| ADC/DCA, /Sensor Required | N/R** | N/R** | Yes | No | Yes | Yes | **No** |
| VOC Sampling Required | Yes | Yes | Yes | No | Yes | Yes | **No** |
| Peak MPPT Efficiency | 99% | N/R** | N/R** | 97% | 94% | 80% | **98%** |
| Quiescent Current (μA) | 3 | N/R** | N/R** | 0.9 | 0.3 | N/R** | **0.17** |
| Dimension ($mm^2$) | 5.5 | 1.3* | 0.21 | 1.07 | 14 | 3.11 | **0.47** |
| $P_{IC}/P_{FBR}@\eta_F$ | 1X*@No | 4.4X@89%/94% | 6.5X-9.3X@89% | 4.17X@86% | 3.28X@No | 3.2X@No | **7.38X@82%** |

*Estimated from the paper
**N/R: not reported

**Figure 30.3.6: Comparison table of proposed duty cycle based MPPT and state-of-the-art MPPT techniques.**

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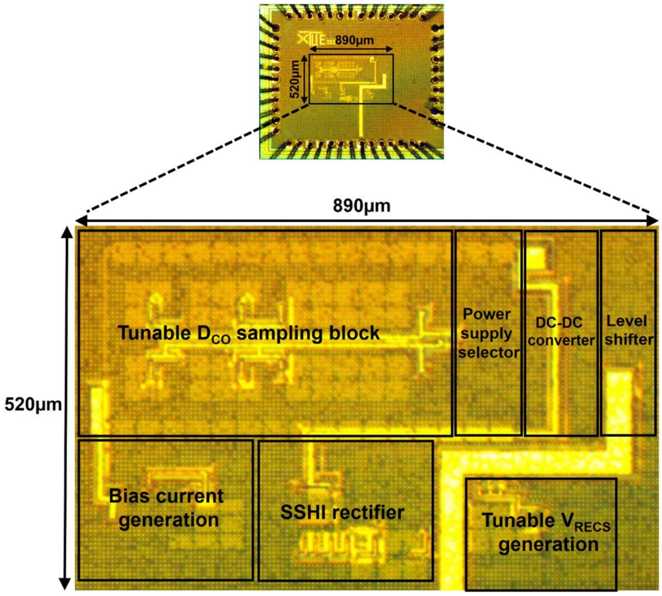


**Figure 30.3.7: Die micrograph.**