Real-world evaluation of a self-startup SSHI rectifier for piezoelectric vibration energy harvesting

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**A R T I C L E   I N F O**

Article history:
Received 9 March 2017
Received in revised form 24 July 2017
Accepted 26 July 2017
Available online 2 August 2017

Keywords:
Energy harvesting
SSHI (synchronized switch harvesting on inductor)
Piezoelectric transducer
Rectification
Power conditioning

**A B S T R A C T**

This paper presents an enhanced SSHI (synchronized switch harvesting on inductor) rectifier with startup circuit and representative environment validation using real world vibration data collected from a tram. Compared to a conventional SSHI rectifier, the proposed rectifier dynamically monitors the working status of the circuit and restarts it when necessary. The proposed rectifier is designed in a 0.35 μm HV CMOS process and its performance is experimentally evaluated. With a 500-s real-world collected vibration data, the conventional and the proposed SSHI rectifiers record average power performance improvements by 9.2× and 22× respectively, compared to a passive full-bridge rectifier. As the startup circuit helps restart the SSHI rectifier several times, it is able to extract energy in an increased excitation range and its average power output performance is 2.4× higher than a conventional SSHI rectifier.

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1. Introduction

As the Internet of Everything (IoE) continues to emerge, powering billions of distributed sensors becomes a big challenge. In the past decade, harvesting ambient vibration energy to power wireless sensor nodes and portable or wearable devices has attracted much research interest [1,2]. Harvested electrical power for most of MEMS or macroscopic harvesters varies from 10s 𝜇W to 10s mW depending on the scale and structure of harvesters [3,4]. Although the raw electrical output power is promising to power most low-power sensors, the stable DC electrical power, ready to be used for loads, significantly depends on the performance of the interface circuit to be employed [5,6].

Full-bridge rectifiers (FBR) are commonly used in commercial energy harvesting systems and the circuit diagram is shown in Fig. 1 [7–9]. The piezoelectric transducer (PT) is modeled as a current source $I_p$ in parallel with a capacitor $C_P$ and a resistor $R_P$. The FBR contains four diodes with a forward voltage drop noting as $V_D$ and a storage capacitor $C_S$. In the associated waveforms, $V_{PFF}$ is the voltage across the PT. It can be seen that $V_{PFF}$ needs to flipped from $-(V_S + V_D)$ to $V_S + V_D$, or vice-versa, to overcome the threshold set by the FBR to transfer energy to $C_S$. Hence, the energy (or electrical charge) used to charge the internal capacitor $C_P$ between these two voltages levels is wasted. The wasted charge is shown as black areas in the waveform. If the excitation vibration level is low such that $V_{OC\text{(pp)}} < 2(V_S + 2V_D)$, all harvested energy is wasted, where $V_{OC\text{(pp)}}$ is the open-circuit peak-to-peak voltage of $V_{PFF}$. If $V_{OC\text{(pp)}}$ marginally overcomes the threshold, most of harvested energy is wasted and the power efficiency in this case is extremely low.

In order to increase the power extraction efficiency, many active rectifiers have been introduced to use inductors to improve the performance [10–15]. SSHI (synchronized switch harvesting on inductor) is one of the most efficient rectifiers using an RLC loop to synchronously flip the voltage $V_{PFF}$, hence increase the power efficiency [16–19]. Fig. 2 shows the circuit diagram and associated waveforms of an SSHI rectifier. The inductor is controlled by analog switches, which are driven by a synchronous pulse signal $\phi_{SSHI}$. From the waveform, it can be seen that a $\phi_{SSHI}$ pulse is generated for each zero-crossing moment of $I_p$. During the pulse of $\phi_{SSHI}$, $V_{PFF}$ is flipped in the RLC system with some loss due to the parasitic resistance. As the RLC oscillation loop helps flip $V_{PFF}$, the wasted charge, shown as black areas, is significantly decreased.

Fig. 3a shows a simplified architecture of an SSHI rectifier, which contains a FBR, a zero-crossing detection block, a pulse generation block and a level-shifter. When $I_p$ is close to zero, the diodes of the FBR are just about to turn OFF. At this moment, one of $V_p$ and $V_N$ begins to increase from $-V_D$ and the other one begins to decrease from $V_S + V_D$. One common method to detect the zero-crossing moment of $I_p$ is using two comparators to compare $V_p$ and $V_N$ with a reference voltage $V_{ref}$. This reference voltage is set slightly higher than $-V_D$ and it aims to finds the moment while $V_p$ or $V_N$ begins to increase from $-V_D$. The outputs of the two comparators

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http://dx.doi.org/10.1016/j.sna.2017.07.050
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Fig. 1. Full-bridge rectifier and the associated waveforms.

Fig. 2. SSHI rectifier and the associated waveforms.

Fig. 3. Circuit diagram of an SSHI rectifier and the associated waveforms.
are ANDed and the resulting signal SYN presents a synchronous signal to control the switch. For each zero-crossing moment of \( I_p \), a rising edge is generated in SYN and it is used to generate a pulse in the following blocks to control the inductor. In the proposed rectifier, SYN is also used in a startup circuit, which will be presented in the next section.

The voltage loss after the flip is noted as \( V_F \), as shown in Fig. 2, which depends on the inductance, parasitic resistance and \( C_p \) and it can be expressed as:

\[
V_F = (V_S + 2V_D) \left( 1 - e^{-\frac{2C_p}{Lc}} \right)
\]

In order to keep generating rising edges in SYN, \( V_{PP} \) needs to attain \( V_S + 2V_D \) or \(- (V_S + 2V_D)\). Hence, the condition for the SSSI rectifier to sustain operation is:

\[
V_{OC(PP)} > V_F
\]  

(1)

Fig. 3b shows the waveforms of the conventional SSSI rectifier. The SSSI rectifier is operating well while the excitation level satisfies the condition in (1). However, while the excitation goes to a near-zero level for a period of time, both \( V_P \) and \( V_N \) tend to \( \frac{1}{2} V_S \) and they oscillate near this value if weak excitation is present. During this time, \( V_{PP} \) tends to zero. In this case, SYN keeps high and there is no rising edge generated to flip \( V_{PP} \). In order to start flipping \( V_{PP} \) again for each zero-crossing moment of \( I_p \), either \( V_P \) or \( V_N \) should attain \( - V_D \) to trigger one of the two comparators in the zero-crossing detection block. This is also the condition that \( V_{PP} \) attains \( V_S + 2V_D \) or \(- (V_S + 2V_D)\). Hence, after the SSSI rectifier stops working, the condition for it to restart is:

\[
V_{OC(PP)} > 2(V_S + 2V_D)
\]  

(2)

Comparing the two conditions in (1) and (2), the condition to restart is much more difficult to be satisfied than the condition to sustain. Hence, the vibration energy between these two excitation levels is completely wasted for conventional SSSI rectifiers if it is not started [20]. This paper proposed an enhanced SSSI rectifier with a startup circuit and the fabricated chip is experimentally evaluated with a 500-s real-world collected vibration data from a tram in Birmingham, UK. The real-world performance of the conventional SSSI and proposed SSSI circuits are compared to see the obvious improvement by adding a startup circuit.

2. Proposed SSSI rectifier

Fig. 4 shows the block architecture of the proposed SSSI rectifier with startup circuit, which consists of a conventional SSSI rectifier and a startup circuit. The startup circuit contains three main blocks: monitoring block, evaluation block and startup block. The monitoring block monitors the working status of the conventional SSSI rectifier and it outputs a signal \( WKG \) indicating if the voltage across the piezoelectric transducer (PT), \( V_{PP} \), is being correctly flipped for each zero-crossing moment. If \( WKG \) goes low, the evaluation block starts evaluating the ambient excitation level and stability to determine when the SSSI rectifier needs to be restarted. Once it confirms that a startup operation can be performed, a \( STARTUP \) signal is generated to let the following startup block to restart the SSSI rectifier.

The circuit diagram of the monitoring block is shown in Fig. 5, where there are a digital counter and a D-flip-flop. While the SSSI rectifier is working, SYN goes high and low periodically and it resets the counter and sets the output \( WKG \) to high. While the SSSI rectifier is not working, SYN stays high. In this case, the counter cannot be reset until it counts to a preset value, which reset \( WKG \) to low level indicating that the SSSI rectifier is not working.

Fig. 6 shows the circuit implementation of the evaluation block, which evaluates the excitation level and excitation stability. (1) indicates the condition for a conventional SSSI rectifier to keep working. Hence, this condition should first be satisfied before restarting the SSSI. This evaluation is performed in the stage 1 by comparing fractions of \( V_P \) and \( V_S \). The condition in (1) can be rewritten as \( V_P > \frac{1}{2} V_S + \frac{1}{2} V_F \) or \( V_P < \frac{1}{2} V_S - \frac{1}{2} V_F \) because \( V_{PP} = V_P - V_N \) and both \( V_P \) and \( V_N \) are centered at \( \frac{1}{2} V_S \). Choosing \( V_P < \frac{1}{2} V_S - \frac{1}{2} V_F \) as the evaluation condition, it can be further rewritten as:

\[
V_P < \frac{1}{2} V_S - \frac{V_S}{4} \left( 1 - e^{-\frac{C_P}{2C}} \right) \Rightarrow V_P < \frac{1}{4} V_S \left( 1 + e^{-\frac{C_P}{2C}} \right)
\]

(3)
In some cases the SSSI rectifier can be self-started without using the proposed startup circuit. If the shock or excitation level is high such that the condition in (2) is met, a SYN signal will instantly be generated and the WKG signal goes to high immediately. In this case, the conventional SSSI circuit is self-started without using the startup circuit. However, as previously mentioned, the excitation level required to satisfy (2) is very high, so self-startup is very hard to be achieved in real-world implementations. Experiments with a real-world vibration source will present how the proposed startup circuit improve the overall energy efficiency in the next section.

3. Measurement results

The proposed rectifier is designed and fabricated in 0.35μm HV CMOS process and the die photo is shown in Fig. 8. The proposed rectifier contains a conventional SSSI rectifier and a startup circuit. Hence experiments on both the conventional and the proposed SSSI can be performed with the chip by disabling and enabling the startup circuit to compare the performance. The power consumption of the chip is 0.8 μW while the SSSI rectifier is operating. After the SSSI rectifier stops operation, the consumption goes down to 0.65 μW as the voltage-flipping signal φSSSI is not generating in this case to drive the analog switches.

Unlike majority of the previous work in the literature, experimental measurements did not simply employ a sine wave excitation in order to realize the representative environment validation. This is because real-world ambient vibration is rarely that of a pure sine wave, and is typically broadband, noisy and time-varying in nature. Hence, performing experiments with real-world collected data can better present the performance improvement.
of the proposed SSHI rectifier compared to the full-bridge rectifier
and the conventional SSHI rectifiers.

Fig. 9 shows the vibration data collected from the undercarriage
of a tram in Birmingham, United Kingdom. The data was measured
using a digital accelerometer (Analog Devices ADXL345) integrated
with a data logger (Gulf Coast X16–2) with a sampling rate at 400 Hz.
The data lasts for 500 s and it can be seen that it is very noisy
and the vibration amplitude randomly varies with time. Eight time
moments, t1 to t8, are labeled in the figure to facilitate explanations.
The two zoomed-in figures show short periods at 35 s
and 75 s while the tram is stationary and moving, respectively. Fig. 10
shows the STFT (Short-time Fourier Transform) plot of the vibration
data. Comparing the two figure, it can be seen that the low amplitude
periods (t1, t2, t6 and t8) shown in Fig. 9 represents the time
while the tram stops. These are either due to tram stations
(t1, t3 and t8) or traffic lights (t6). It can be observed from the STFT
plot that while the tram is moving, the vibration frequency is
centered and peaked at around 65 Hz; however, while the tram stops,
the vibration is very noisy and is no longer centered to any specific
frequencies. This phenomena can also be observed from the two
zoomed-in figures in Fig. 9. While the tram is stationary (left subfigure),
the captured acceleration data is very noisy and while the tram is moving (right sub-figure), the data looks more like a sinusoidal signal of frequency around 65 Hz with a little noise. In terms of the vibration amplitude, it varies for different periods while the tram is moving. For example, the amplitudes at t2, t6 and t7 are relatively low but the amplitude at t4 is much higher. This can be due to rail track conditions and the speed of the tram.

The measurements were performed using a commercially avail-
able cantilevered piezoelectric harvester (Mide Technology V20W)
with the nature frequency of 82 Hz. In order to use this piezoelectric
transducer (PT) with the vibration data shown in Fig. 10, the natural
frequency of this PT was tuned to 65 Hz by adding a tiny tip mass.
Fig. 11 shows the experimental setup. The 500-s vibration data
was downloaded into a waveform generator (Agilent Technologies
33250A 80 MHz waveform generator) and the signal was amplified
by a power amplifier (LDS PA100E Power Amplifier) to match
the acceleration level with the real-world vibration. The modified
piezoelectric harvester was then excited on a shaker (LDS V406
M4-CE) driven by the signal to test different interface circuits.

First, the vibration data is used to measure the performance of a
passive full-bridge rectifier (FBR). As the threshold to extract energy
for a FBR is high as given in (2), only the short period with high excita-
tion level (around t4 in Fig. 9) attains the threshold. However, as
most of energy is wasted due to flipping the voltage, the power
efficiency is extremely low in this case. Measurements show that
V2 is increased from 2.91 V to 2.96 V in this 500-s measurement.
C3 is a super capacitor (AVX BestCap B205CA1032SB) with mea-
sured capacitance C3 = 5.2 mF, so the energy extracted in this 500 s
is \( \frac{1}{2} C_3 (2.96^2 - 2.91^2) = 0.76 \text{ mJ} \) and the average power over the
500 s is 1.53 \( \mu \text{W} \).

In order to make fair comparisons of different circuits, V2 is set
to be around 3 V before charging starts. Although different circuits
require different V2 values to achieve their maximum power points
(MPP) and V2 \( \approx 3 \text{ V} \) may not be the optimal value, the initial value
V2 \( \approx 3 \text{ V} \) is chosen because it is believed to be around the preferred
supply voltages of most wireless sensors, which require stable DC
supplies between 1.8 V and 5 V.

The conventional SSHI rectifier without startup circuit is then
tested. Fig. 12 shows measured waveforms for 500 s. The signal Vp
is the voltage at one electrode of the harvester. \( \phi_{SSHI} \) is the inductor-
control signal to flip the voltage across the harvester. WKG is the
signal indicating if the SSHI rectifier is working and V2 is the voltage
across the storage capacitor C3 connected at the output of the full-
bridge rectifier. These signals are also labeled in Fig. 4.

At t4, the SSHI rectifier is not working as the tram stops; hence,
\( \phi_{SSHI} \) is not generated, WKG keeps at low and no energy is trans-
ferred into C3. Although the tram starts moving at t5, the condition
for the conventional SSHI to start working is still not satisfied as
the required excitation level is high as shown in (2). At t6, the tram
starts moving again and the excitation level at this moment is high
(refer to t4 in Fig. 9). The condition in (2) is satisfied and the con-
ventional SSHI rectifier is started. Therefore, the voltage across
the PT is correctly flipped by the signal \( \phi_{SSHI} \) and WKG goes high. V2 is
also increased as charge flows into C3. From Fig. 9, it can be seen that,
after a short period of high excitation, the excitation level is decreased at t5 although the tram still keeps moving. However,
the conventional SSHI rectifier does not stop working because it is
already started and the condition to sustain its operation is much
lower as expressed in (1). Then the tram stops due to the traffic
lights at t6 and the rectifier stops working. Once the SSHI rectifier
stops working, the condition to restart it is now again difficult to
be satisfied. Hence, the following moderate excitation level after
the tram starts moving at t3 cannot restart the conventional SSHI
rectifier and the vibration energy during this period is wasted.

During this 500-s measurement, the storage capacitor C3
is charged from 2.95 V to 3.43 V. Hence, the energy extracted by the
circuit is \( \frac{1}{2} C_3 (3.43^2 - 2.95^2) = 7.344 \text{ mJ} \) and the average electrical
power over the 500 s is 14.68 \( \mu \text{W} \). In addition, as previously mea-
sured, the power consumption of the chip is 0.8 \( \mu \text{W} \) while SSHI is
operating and 0.65 \( \mu \text{W} \) while SSHI is not operating. The average
power consumption in this 500 s can be estimated to be around
0.68 \( \mu \text{W} \) by estimating the duty ratio while SSHI is operating (high
WKG signal). Hence, the net output power by a conventional SSHI
rectifier is around 14 \( \mu \text{W} \).

The same vibration data is used again to test the proposed SSHI
rectifier with startup circuit. Fig. 13 shows the waveforms, where
there are five signals. The signals are labeled in the system archi-
tecture in Fig. 4 and the last signal STARTUP is the signal sent
a the startup block to restart the SSHI circuit. From the signal Vp,
it can be seen that there is a short impulse at the beginning. As this
impulse is too short, the evaluation block (Fig. 6) does not approve
a restart operation. The tram starts moving from t1 and the eval-
uation block begins to evaluate the amplitude and duration of the
excitation. After a short period of time at t2, the excitation is evalu-
ated as high and stable; hence a STARTUP pulse is generated and

![Fig. 8. Die photo of the proposed SSHI rectifier.](image)
During the 500 s measurement, $V_S$ is increased from 2.92 V to 3.89 V, hence the extracted energy is calculated as 17.2 mJ and the average power is 34.4 $\mu$W. In addition, the average quiescent power consumption of the chip in this 500 s is estimated to be around 0.73 $\mu$W. Therefore, the net output power of the proposed SSHI rectifier is 33.67 $\mu$W.

4. Conclusion

This paper proposes an enhanced SSHI rectifier with startup circuits and it is implemented in a real-world vibration environment. The chip is designed in a 0.35 $\mu$m CMOS process. Instead of using the SSHI rectifier is restarted. During the remaining time while the tram is moving, WKG keeps high and $\phi_{SSH}$ pulses are generated to flip the voltage until the tram stops. At $t_3$, the tram starts moving again. As the excitation level at this moment is sufficiently high so that the condition in (2) is satisfied, the SSHI rectifier is directly self-started without using the startup circuit. The startup mechanism at this moment is the same as the conventional SSHI rectifier. Hence, neither the short evaluation period nor the STARTUP pulse is present at this time. During the short stop of waiting for traffic lights, the SSHI rectifier stops working again. While the tram starts moving at $t_6$, the startup circuit starts evaluating the excitation and another STARTUP pulse is generated at $t_5$ to restart the SSHI rectifier.

Fig. 9. Time-domain acceleration plots of the measured real-world vibration data of length 500 s collected from a tram in Birmingham, UK.

Fig. 10. STFT (Short-time Fourier Transform) plot of the vibration data.
Fig. 11. Experimental setup.

Fig. 12. Waveforms of the conventional SSHI rectifier.

Fig. 13. Waveforms of the proposed SSHI rectifier with startup circuit.
a sine wave excitation signal, the chip is experimentally evaluated under the excitation of a 500-s real-world collected vibration data from a tram in Birmingham, UK. The real-world vibration data is much noisier than a sine wave signal and the excitation level is highly unpredictable. The measured results shows that the proposed SSHI rectifier is able to operate in an increased excitation range and extract more power compared to conventional SSHI rectifiers. During the 500-s measurements, the startup circuit helps the SSHI rectifier restart twice and the total extracted energy is 2.4× higher than the conventional SSHI circuit. Compared to a passive full-bridge rectifier, the conventional and the proposed SSHI rectifiers improve the performance by 9.2× and 22×, respectively.

Biographies

Sijun Du received the B.Eng. degree in electrical engineering from University Pierre and Marie Curie, Paris, France, in 2011 and the M.Sc. degree in Electrical Electronics Engineering from Imperial College, London, UK., in 2012. He worked at the Laboratory LIP of University Phoebus in 2015. He joined as a digital IC engineer in Shanghai between 2012 and 2014. He is currently working towards the Ph.D. Degree at the University of Cambridge, U.K., where he is affiliated with the Cambridge Nanoscience Centre. His research interests include energy harvesters and associated interfaces, power electronics, power management circuits, DC-DC converters and rectification circuits.

Yu Jia is currently a Lecturer in Mechanical Engineering at the University of Chester, and leads the Smart Microsystems Research Group. Yu Jia received a First Class (Honours) degree in MEng in electromechnical Engineer- ing from the University of Southampton in 2010, and PhD in Engineering from the University of Cambridge in 2014. He was then a Research Associate at Cambridge for a year. He is the co-founder of 8power Ltd. He is also a steering board member of the Energy Harvesting Network. His research interests involve vibration energy harvesting, micro-electromechanical systems, nonlinear vibration dynamics and smart integrated systems.

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Funding

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/L010917/1 and EP/N021614/1].

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