A self-powered PSSHI and SECE hybrid rectifier for piezoelectric energy harvesting

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Abstract A hybrid rectifier integrating the parallel-type synchronized switching harvesting on inductor (PSSHI) and synchronous electric charge extraction (SECE) is proposed. The hybrid rectifier can self-adjust its operations between Flipping/SECE and PSSHI/SECE according to the input PE voltage. Furthermore, a simple circuit implementation with the capability of cold-start and self-power is presented. The prototyped rectifier can extract the peak power of 85.7 μW with the PE open-circuit voltage of 3 V and the rectified voltage of 4.14 V. Its performance is at least twice that of the full-wave bridge rectifier in terms of peak output power and operating voltage range. It can cold-start successfully from a lower PE voltage and charge the load to a higher voltage.

Keywords: energy harvesting, piezoelectric, PSSHI, SECE, hybrid, cold-start

Classification: Energy harvesting devices, circuits and modules

1. Introduction

The sustainable power supply of outdoor wireless sensor network (WSN) nodes has emerged as a critical problem in the field of internet of things (IoT) [1]. One promising solution, called vibration energy harvesting (VEH), can harvest vibration energy from environment and convert it into electrical energy for WSN nodes [2]. VEH based on piezoelectric (PE) transducers has attracted most interests since it can directly convert the applied strain into electric charges [3]. However, the ac output voltage and capacitive impedance of PE harvesters bring challenges to the utilization of PE energy. So far, various PE energy extraction schemes have been proposed, covering different operating principles, circuit typologies, implementation processes, etc [4, 5, 6].

The synchronized switching harvesting on inductor (SSHI) [7], and synchronous electric charge extraction (SECE) [8] are two popular nonlinear energy extraction techniques in this field. In fact, the similar techniques were also used in the field of vibration control [9, 10]. The SSHI is divided into series-type and parallel-type according to the location of inductor, called SSSHI and PSSHI, respectively. The SSSHI extracts PE energy and flips PE voltage simultaneously, which is more suitable for high input PE voltage. In contrast, the PSSHI firstly extracts PE energy and then flips PE voltage, which is more suitable for low input PE voltages [11, 12]. The advantage of SSHI has been validated in weakly-coupled PE harvesters [13]. A high quality SSHI rectifier can produce the peak power six times of a full-wave bridge (FB) rectifier [14]. However, the output power of a SSHI rectifier can be seriously influenced by the connected load. Thus, some modified techniques added voltage regulators after SSHI rectifiers to stabilize the output power [15, 16]. As a comparison, the SECE extracts PE energy independent of load by dividing the extraction process into two stages. It firstly transfers the PE energy to an external inductor, then delivers the inductor energy to the load. The power improvement of a high quality SECE rectifier can exceed three times compared to the FB technique [17]. Similarly, the advantage of SECE is only valid in moderately and weakly-coupled PE harvesters. Hence, some improved techniques were developed for strongly-coupled cases [18, 19, 20].

The key behind SSHI and SECE is to flip the PE voltage by using LC oscillation. The difference is the LC oscillation in SSHI keeps for 1/2 LC period, whereas it is approximately 1/4 LC period in SECE. The quality of LC oscillation can affect the performance seriously. Additionally, the desired LC oscillation can be implemented using the self-powered switch breaker circuits [21, 22, 23, 24, 25], or active control circuits [26, 27, 28, 29, 30, 31, 32, 33, 34]. The former implementations can cold-start only with the input PE energy, but the switching delay due to discrete components is usually unavoidable [35]. The latter implementations can achieve the accurate switching control but at the cost of additional power consumption. Although the SSHI, SECE and their variants have been intensively investigated, there is relatively little research on the combination of these fundamental techniques. As an attempt, some recent works proposed the so-called synchronous inversion and charge extraction (SICE) technique [36, 37, 38]. The SICE only flips the PE voltage in one half-cycle of vibration, and extracts the PE energy in the other half-cycle, which combines the flipping operation and SECE operation together. Their works showed that the SICE technique can improve the extraction efficiency at low output voltages under weak excitation. However, limited by its operating principle, it can only extract the PE energy once in a complete vibration cycle, whereas other techniques usually can perform energy extraction twice. Also, the critical issues of cold-start and self-power seem to have not been addressed in their presented circuit implementations.

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Previous works have demonstrated that the advantages of SSSH and SECE are in the peak output power and operating voltage range, respectively. Therefore, this Letter proposes a self-powered hybrid rectifier for weakly-coupled PE harvesters, which combines PSSH and SECE together to take their individual advantages. Moreover, the proposed hybrid rectifier can self-adjust its operations adaptively according to the input PE voltage. Also, the implementation of the hybrid rectifier is based on a very simple circuit topology with a reduced switching delay. Additionally, the presented circuit implementation allows it to cold-start only with the input PE energy, and to achieve fully self-powered operations.

2. Proposed self-powered PSSH and SECE hybrid rectifier

The conceptual circuit of the proposed PSSH and SECE hybrid rectifier is shown in Fig. 1(a), of which the weakly-coupled PE harvester is presented as an ac current \( i_p \) parallel with a capacitor \( C_p \). The hybrid rectifier can have at most five typical operating stages in one complete cycle. The detailed operations depend on the input PE voltage \( v_p \) and the rectified voltage \( V_r \) together.

If \( v_p \) is lower than \( V_r \), there only exists four operating stages, and the stage 2 is absent. The predicted waveform is plotted in the time duration from 0 to \( t_1 \) in Fig. 1(b). During the positive half-cycle \( (v_p < 0) \), the PE voltage \( v_p \) increases as \( i_p \) charges \( C_p \) forward at the stage 1. When \( v_p \) reaches to its positive peak \( v_p \) \( p_{\text{max}} \), the switch \( S \) can conduct to trigger LC oscillation at the stage 3. The LC oscillation can continue for \( 1/2 \) \( LC \) period and flip the PE voltage from \( V_1 \) to \( V_2 \).

Because the peak voltage \( V_p^{\text{max}} \) is still lower than \( V_r \) during this half-cycle, the diode \( D_1 \) cannot conduct so that no PE energy can be transferred to the load. During the negative half-cycle \( (v_p < 0) \), the PE voltage \( v_p \) increases reversely as \( i_p \) charges \( C_p \) backward at the stage 4. When \( v_p \) reaches to its negative peak \( V_p^{\text{min}} \), the switch \( S \) can conduct to trigger \( LC \) oscillation at the stage 5. In detail, the stage 5 consists of two substages. The first substage is \( C_p \) pre-charging the inductor \( L \) and causing the PE voltage to flip from \( V_3 \) to \( V_4 \). It continues for \( 1/4 \) \( LC \) period approximately. The second substage is the inductor \( L \) releasing its stored energy to the storage capacitor \( C_p \) through a typical freewheeling operation. Therefore, the circuit can transfer PE energy to the load during this half-cycle. Actually, the whole behaviors of the hybrid rectifier are the same with the published SICE rectifier when the PE voltage \( v_p \) is lower than the rectified voltage \( V_r \).

The above four operating stages can improve the PE voltage gradually until the PE voltage \( v_p \) reaches to \( V_r \). As a consequence, the condition of \( v_p \) being higher than \( V_r \) can be reached finally even though the initial PE voltage is low. For this case, there exists five operating stages in one complete cycle. The predicted waveform is plotted in the time duration from \( t_1 \) to \( t_2 \) in Fig. 1(b). Since the stage 2 is available, the PE harvester can charge the storage capacitor \( C_p \) directly through \( D_1 \). Thus, the PE energy can be extracted during the positive half-cycle of \( v_p \). When the PE voltage \( v_p \) is going to decrease, the switch \( S \) can conduct to trigger \( LC \) oscillation at the stage 3. Indeed, the operations during the positive half-cycle are consistent with the behaviors of a PSSH rectifier. Furthermore, the operations during the negative half-cycle are the same with the previous case, which behaves like a SECE rectifier. Therefore, the proposed hybrid rectifier is not only suitable for the low input PE voltages, but also for the high input PE voltages. Accordingly, it can self-adjust its operations adaptively according to the input PE voltage, and enter the PSSH/SECE hybrid working mode eventually.

The benefit of the proposed hybrid rectifier is to take the individual advantages of PSSH and SECE together. As can be seen from Fig. 1(b), the PSSH operation directly transfers part of the PE energy to \( C_p \), and flips the PE voltage from \( V_1 \) to \( V_2 \) as a favorable bias for next SECE operation. Also, the SECE operation transfers the partial PE energy but in a decoupling way, and flips the PE voltage from \( V_3 \) to \( V_4 \) to provide a favorable bias for next SICE operation. For a weakly-coupled PE harvester, the current \( i_p \) can be considered to be stable and independent of the connected load. Assume the current \( i_p \) is equal to \( I_p \sin \omega t \) in which \( I_p \) is the amplitude and \( \omega \) is the angular frequency. Then, the PE open-circuit voltage \( V_{p,\infty} \) equals to \( I_p/(\omega C_p) \). Theoretically, the energy extracted during the PSSH and SECE operations can be calculated by (1) and (2), respectively, whereas \( Q_L \) is the quality factor of the \( LC \) oscillation. The voltage \( V_4 \) is the corresponding PE voltage after the SECE operation, and it may be equal to or smaller than \( V_r \). If \( V_4 \) is equal to \( V_r \), the stage 1 and stage 2 can be merged together as one stage.

\[
E_{\text{pssh}} = \begin{cases} 
0, & v_p < V_r \\
\frac{1}{2} \omega V_r I_p + C_p V_r (V_4 - V_r), & v_p \geq V_r 
\end{cases}
\]
Fig. 2 presents the circuit implementation of the proposed PSSHII and SECE hybrid rectifier. It is based on a very simple topology with a reduced switching delay, and has the capability to cold-start and self-power. The components \( C_d1, NM1-NM3, R_d, Q_1, Q_3 \) constitutes a low delay synchronized switch for the positive half-cycle of \( V_p \), and \( C_d2, PM1-PM3, R_d, Q_2, Q_4 \) constitutes the other low delay synchronized switch for the negative half-cycle of \( V_p \). These MOSFETs are gate-source short-circuited and used as diodes with a fixed forward voltage drop. The \( NM2, NM3 \) and \( PM2, PM3 \) are inserted to reduce the switching delay. The inserted number depends on the base-emitter voltage drop of \( Q_3 \) and \( Q_4 \), and can be adjusted manually according to the practical conditions.

3. Results and discussion

For a rapid validation, the prototyped hybrid rectifier circuit is fabricated using the conventional discrete components, as listed in Table I. The measurements are performed on a weakly-coupled cantilever-based PE harvester (Steel substrate: \( 250 \times 50 \times 2 \) mm\(^2 \); PE material: PZT-5H, \( 60 \times 31 \times 0.2 \) mm\(^3 \); \( C_p = 180 \) nF).

Fig. 3 shows the measured waveform of the hybrid rectifier under various scenarios. As can be seen, the actual PE voltage corresponding to the synchronized switching point is only 0.3 V below the peak PE voltage. The switching delay of the presented implementation is further reduced compared to the previous implementations. The steady waveform of PE voltage in Fig. 3(a) represents the case of \( V_p \) being smaller than \( V_r \), which is consistent with the previous SICE rectifier. For this case, the hybrid rectifier only extracts the PE energy during the negative half-cycle of \( V_p \), whereas merely flips the PE voltage during the positive half-cycle of \( V_p \). The steady waveform in Fig. 3(b) indicates the case of \( V_p \) being larger than \( V_r \), which combines the PSSHII and SECE operations together. For this case, the hybrid rectifier can transfer the PE energy to the load during both of the positive and negative half-cycles. Finally, the transient waveform in Fig. 3(c) confirms that the hybrid rectifier is able to cold-start only with the input PE energy, and can improve the PE voltage gradually.

Fig. 4 plots the output power (\( P_{\text{hybrid}} \)) of the hybrid rectifier as a function of load resistor \( R_L \) and rectified voltage \( V_r \), respectively. The output power (\( P_{\Omega} \)) of the full-wave bridge (FB) rectifier serves as a benchmark. When the input PE open-circuit voltage \( V_{p,oc} \) is 3 V, the hybrid rectifier can output the peak power of 85.7 µW, while the peak power of

| Table I Used components. |
|--------------------------|
| Component | Type |
| \( NM1-NM3 \) | UT2302G |
| \( PM1-PM3 \) | UT2301G |
| \( Q_1, Q_3 \) | 2N3904 |
| \( Q_2, Q_4 \) | 2N3906 |
| \( D \) | BAT54 |
| \( C_d1, C_d2, C_r, L, R_d \) | 2nF, 2nF, 10µF, 1.5mH, 20mA |

Fig. 3 Measured waveform.

Fig. 4 Power as a function of load resistor \( R_L \) and rectified voltage \( V_r \).
the FB rectifier is only 39.8 μW. The performance of the FB rectifier with $V_{p,oc}$ of 3 V is close to that of the hybrid rectifier with $V_{p,oc}$ of 2 V. It means the hybrid rectifier can operate successfully with a lower PE voltage to achieve the same performance. Additionally, the operating voltage range of the hybrid rectifier is at least twice that of the FB rectifier. Thus, the hybrid rectifier is able to charge the load to a higher voltage.

Table II compares the proposed hybrid rectifier with some other PE energy extraction circuits. Previous works [26] and [8] are based on PSSHII and SECE, respectively. The SICE in [38] combines voltage flipping and SECE together to make it more suitable for low input PE voltage. Further, the proposed rectifier can work in Flipping/SECE or PSSSHII/SECE adaptively according to the PE voltage. Additionally, the proposed rectifier is able to cold-start and does not need digital control treatments. With regard to FoM factor, the proposed rectifier achieves $2.3 \times$ under 3 V open-circuit PE voltage and 4.14 V rectified voltage. It is superior to [8] and [26], but is inferior to [38]. However, the SICE rectifier in [38] cannot cold-start without the external power supply. Also, because the SICE in [38] adopts CMOS technology, so it takes a great advantage in power loss. As a whole, the proposed hybrid rectifier demonstrates the advantages in topology, cold-start ability, peak output power and load voltage range.

4. Conclusion

A self-powered PSSSHII and SECE hybrid rectifier with a simple topology has been proposed for PE harvesters. It can perform the voltage flipping and SECE extraction during the positive and negative half-cycles of the PE voltage, respectively, when the PE voltage is lower than the rectified voltage. On the contrary, it can change to perform PSSHII and SECE extraction operations during the two half-cycles when the PE voltage is higher than the rectified voltage. The measurements show that the prototype hybrid rectifier can successfully cold-start and self-power only with the input PE energy. It can extract the maximum power of 85.7 μW from a weakly-coupled PE harvester with the PE open-circuit voltage of 3 V and the rectified voltage of 4.14 V. The performance of the hybrid rectifier is at least twice that of the FB rectifier in terms of peak output power and operating voltage range together. Therefore, the proposed hybrid rectifier can become an alternative rectifier solution for PE energy harvesting.

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