Non-linear AC-DC Converter for Piezoelectric Energy Harvesting Power Supplies

PEHPS-PCB3

Description

The PEHPS-PCB3 includes an AC-DC converter and a buck converter to adapt the AC power from piezoelectric transducers with maximum efficiency for supplying electronic circuits.

The modified parallel SSHI converter employed in the AC-DC converter provides higher efficiencies than a diode bridge. The buck converter with a hysteresis control generates a regulated output voltage between 1.2 V and 25 V for input voltages between 6 V and 42 V.

Features

- High efficient rectifier for piezoelectric transducers with buck converter
- Input voltage range: 4 V to 60 V for AC-DC conversion with unregulated DC output voltage
- Input voltage range: 6 V to 42 V for AC-DC conversion with regulated DC output voltage
- DC regulated output voltage range: 1.2 V to 25 V

Applications

- Energy Harvesting with piezoelectric elements
- Energy Harvesting from vibrations
- Battery-free power supply for sensors, wireless sensor networks and low power RF devices
Fig. 1: Dimensions of the PEHPS-PCB3 and location of some of its components

### Pin Configuration

<table>
<thead>
<tr>
<th>Pin number</th>
<th>Pin name</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1-1</td>
<td>PZ1</td>
</tr>
<tr>
<td>X1-2</td>
<td>PZ2</td>
</tr>
<tr>
<td>X2-1</td>
<td>OUT1</td>
</tr>
<tr>
<td>X2-2</td>
<td>GND</td>
</tr>
<tr>
<td>X3-1</td>
<td>GND</td>
</tr>
<tr>
<td>X3-2</td>
<td>OUT2</td>
</tr>
</tbody>
</table>

### Electrical Characteristics

The absolute maximum ratings of $V_{PZ}$ and $V_{OUT1}$ depend on jumper JP9:

- $V_{PZ}$
  - JP9 open: 60 V
  - JP9 closed: 42 V

- $V_{OUT1}$
  - JP9 open: 57.3 V
  - JP9 closed: 40 V

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Min.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric Input Voltage</td>
<td>$V_{PZ}$</td>
<td>JP9 open</td>
<td>4</td>
<td>60</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP9 closed</td>
<td>6</td>
<td>42</td>
<td>V</td>
</tr>
<tr>
<td>Unregulated DC Output Voltage range</td>
<td>$V_{OUT1}$</td>
<td>JP9 open</td>
<td>57.3</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP9 closed</td>
<td></td>
<td>40</td>
<td>V</td>
</tr>
<tr>
<td>Regulated DC Output Voltage</td>
<td>$V_{OUT2}$</td>
<td>1.2</td>
<td>25</td>
<td></td>
<td>V</td>
</tr>
</tbody>
</table>

*Table 1. Electrical characteristics of the PEHPS-PCB3*
Typical Performance Characteristics

The output power (pins X2-1, X2-2) as a function of the load connected for different topologies employing a piezoelectric element (P-876.A12 from the company Invent GmbH at 16.7 Hz) is displayed in Fig. 2. The AC curve is obtained connecting the piezoelectric element to a resistor without any rectification. The diode bridge curve is measured connecting the piezoelectric element to a diode bridge for the rectification of the piezoelectric power. The PEHPS-PCB3 curve is obtained employing the PEHPS-PCB3.

![Fig. 2: Harvested power as a function of the load for different topologies employing a piezoelectric element at 16.7 Hz.](image)

**Block Diagram**

![Fig. 3: SSHE AC-DC converter](image)
Pins and Jumpers Functionality

X1 is the connector for the piezoelectric element.
X2 is the output connector of the SSHI AC-DC converter. It provides an unregulated DC output, OUT1.
X3 is the regulated output voltage OUT2 of the buck-converter placed after the AC-DC converter.
JP3 connects the inductor L1 to the SSHI converter.
JP2 connects inductor L2 and L3 to the SSHI converter.
JP12 connects the input of the linear regulator to the unregulated output OUT1.
JP8 connects the output of the linear regulator to the positive supply of the comparator with hysteresis.
JP11 connects the unregulated output OUT1 to the input of the comparator with hysteresis.
JP9 connects the unregulated output OUT1 to the input of the step-down converter.
JP10 connects the output of the comparator with hysteresis to the enable pin of the step-down converter.

Detailed Description

Two block diagrams of the PEH-PCB3 are shown in Fig. 3 and 4. The board consists of a modified parallel SSHI converter that rectifies the AC power provided by the piezoelectric transducer and a buck converter that reduces the rectified voltage. A control circuit switches the two MOSFETs of the rectifier bridge. This control circuit is frequency dependent which implies that capacitor \( C_6 \) has to be adjusted. It is possible to connect four different inductors to the SSHI converter in order to test which configuration is more efficient for the piezoelectric transducer and the mechanical energy applied.

Capacitor \( C_5 \) is the output capacitor of the unregulated DC output voltage of pins X2-1 and X2-2 and filters the rectified signal. For the case of a vibration of 17 Hz, the filter capacitor of the series SSHI converter is \( C_5 = 4.7 \, \mu F \) but the same capacitance provides a substantial output voltage ripple for the case of 3 Hz, and therefore \( C_5 = 14 \, \mu F \) is appropriate.
The buck converter with low quiescent current provides a regulated output voltage. This buck converter is enabled via a low-power comparator with hysteresis to harvest the power of the piezoelectric transducer at its maximum power point. The threshold voltages of the comparator can be slightly modified through trimmers $R_7$ and $R_{14}$ and are set to 5.5 V and 11 V. If another threshold voltage is needed, new values for resistors $R_7$, $R_8$, $R_9$, $R_{11}$ and $R_{14}$ have to be found following these equations:

$$R_7 + R_8 + R_9 = 4.3 \times 10^6 \left( \frac{V_{HB}}{2.5} \right)$$

$$R_{11} + R_{14} = \frac{1}{\frac{V_{THR}}{1.182 \cdot (R_7 + R_8 + R_9)} - \frac{1}{R_7 + R_8 + R_9} \cdot 4.3 \times 10^6}$$

where $V_{HB}$ is the hysteresis band voltage and $V_{THR}$ is the higher-lever trip value of the hysteresis comparator.

The regulated output voltage delivered on pins X3-2 and X3-1 is 5V and can be slightly modified through trimmer $R_{16}$. If another output voltage is required, the values of $R_{10}$, $R_{13}$, $R_{16}$ and $R_{18}$ have to be modified employing the following equation:

$$R_{10} + R_{13} + R_{16} = R_{18} \left( \frac{V_{OUT}}{1.21} - 1 \right)$$

Capacitor $C_{10}$ is the output capacitor for the regulated DC output voltage.

![Fig. 5: Steady-state operation of the AC-DC rectifier](image)

Fig. 5. shows the steady-state operation of the AC-DC converter where CH1 is the piezoelectric voltage $V_{PZ}$, CH2 corresponds to the signal on the test point P5 of Fig. 3, CH3 is the gate control signal that corresponds to test point P7 on Fig. 3 and CH4 is the unregulated DC output voltage $V_{OUT}$. 
Fig. 6 shows the steady-state operation of the regulated output voltage on pins X3-1 and X3-2 when the unregulated output voltage is always higher than the lower-level trip value of the hysteresis comparator. CH1 is the piezoelectric voltage $V_{\text{PZ}}$, CH2 is the unregulated output voltage $V_{\text{OUT1}}$, CH3 is the EN pin of the step-down converter and CH4 is the regulated output voltage $V_{\text{OUT2}}$.

Fig. 7 presents the steady-state operation of the regulated output voltage for the case that the unregulated output voltage swings to lower voltages than the lower-level trip value of the hysteresis comparator. This situation makes possible to work in the maximum power point of the power harvested by the piezoelectric element. CH1 is the unreglated output voltage $V_{\text{OUT1}}$, CH2 is the EN pin of the step-down converter and CH3 is the regulated output voltage $V_{\text{OUT2}}$. 