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Trigger circuits in battery-less multi-source power management electronics for piezoelectric energy harvesters

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Abstract

With reference to multi-source vibration energy harvesting based on simultaneous use of multiple piezoelectric converters, this work proposes and experimentally validates two innovative power management circuits based on custom trigger circuits to overcome the limitations related to the traditional approaches. The proposed series-like topology allows to power a load from multiple series-connected capacitors, each with different levels of stored energy preventing the reverse current flow in the less charged capacitors. The proposed parallel-like topology is able to extract the energy from each one of multiple converters and charge a single storage capacitor even when the voltage across the storage capacitor becomes larger than the converter output voltages.

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Keywords: Energy harvesting; piezoelectric converter; multi-source power management circuit; electrical output combination; trigger circuit.

1. Introduction

A recent trend to increase the versatility and the converted power of energy harvesting systems consists in the combined use of multiple energy converters embedded in the same mechanical structure [1]. Converters can simultaneously operate from the same energy source, like a vibration piezoelectric Multi-Frequency Converter Array (MFCA) [2], or from different energy sources, such as from solar radiation, thermal gradients and vibrations [3].

Dedicated passive [2, 4] and active [5-7] power management circuits were designed to convey the power provided by each converter into a single energy storage element to power an electronic load. To be fully operative,
active multi-source power management circuits typically require their own power supply, which could be provided either by a start-up circuit directly fed by the outputs of the converters [8], or by an external power supply [9].

On the other hand, passive multi-source power management circuits for piezoelectric converters do not require any external power supply to operate and typically consist in diode-based rectifiers which combine the outputs of the converters in either parallel-like or series-like configurations [2].

When powering a load with the series-like topology shown in Fig. 1a, the storage capacitor $C_{S_i}$ ($i = 1... N$) with the highest energy level reverse charges the other capacitors, with a consequent loss of energy and, as a limiting case, a possible damage of the devices.

In the parallel-like topology shown in Fig. 1b, at any time only the converter $j$-th ($j = 1... N$) with the highest output voltage charges the storage capacitor $C_S$. Moreover, if the voltage across $C_S$ becomes larger than all converter outputs no more charges are collected, and this is ineffective because additional energy potentially available from the converters is not extracted.

To overcome these limitations, this work proposes two innovative multi-source configurations for power management electronics based on custom trigger circuits.

![Fig. 1: Passive series-like (a) and parallel-like (b) topologies of a multi-source power management circuit for N piezoelectric energy converters.](image)

### 2. Multi-source power management circuits

Each piezoelectric converter is connected to a Power Management Unit (PMU) which consists in a diode-based (1N4148) voltage doubler rectifier circuit, a storage capacitor $C_{S_i}$ (22 µF) and a Trigger Circuit (TC). The trigger circuit is a purposely designed analog switch based on a ultra low-power custom CMOS circuit controlled by the hysteretic comparison of the input voltage with two thresholds $V_{TH}$ and $V_{TL}$. The trigger circuit does not require power supply and sink only tens of nanoamperes from the input terminal (IN) to operate. Therefore, the whole system is battery-less.

The proposed series-like power management circuit is shown in Fig. 2. $N$ cascaded PMUs realize the series-like topology by connecting the output terminal (OUT) of each TC$_n$ ($n = 1... N$) to the reference terminal (REF) of the following TC$_{n+1}$, while the load is connected between the reference terminal of TC$_1$ and the output terminal of TC$_N$.

The proposed parallel-like power management circuit is shown in Fig. 3. $N$ alongside PMUs are parallel-like combined by $N$ common-cathode Schottky diodes $D_n$ (BAT85) to block the reverse current flow from the output to the input terminals. The PMUs together with the 100-mH inductor L (TD4 Q3 TAPJ1003F), the 100-µF output capacitor $C_{S_{out}}$ and the Schottky diode $D_{N+1}$ realize an inverting buck-boost power stage. The load is connected to $C_{S_{out}}$ through TC$_{N+1}$.

### 3. Experimental results

The proposed circuits were realized with $N = 2$ and experimentally characterized by emulating the piezoelectric converters with the sinusoidal voltage generators $v_{g1}$ (6 V peak @ 40 Hz) and $v_{g2}$ (4 V peak @ 60 Hz) plus the internal impedance made by the series capacitors $C_{p1} = C_{p2} = 10$ nF. The thresholds $V_{TH}$ and $V_{TL}$ of the trigger circuits TC$_n$ were set to about 2.2 V and 0.3 V, respectively.
As shown in Fig. 4, the series-like topology allows to power the 10-kΩ load only when both TC₁ and TC₂ are closed and the voltage across the load \( v_{\text{load}} \) is the sum of the voltages across the storage capacitors \( v_{CS1} \) and \( v_{CS2} \). The reverse charging of \( C_{S2} \) is avoided by TC₂ which opens as soon as \( v_{CS2} \) drops below \( V_{TL} \).

As shown in Fig. 5, the parallel-like topology extracts the energy from both converters independently, charging the transfer storage capacitors \( C_{S1} \) and \( C_{S2} \). Thanks to the switching of TC₁ and TC₂ on the inductor L when \( v_{CS1} \) and \( v_{CS2} \) respectively reach \( V_{TH} \), the extracted energy is transferred into the storage capacitor \( C_{Sout} \) regardless of the voltage \( v_{CSout} \). The energy transfer lasts only a few milliseconds, and even if simultaneous energy transfers from \( C_{S1} \) and \( C_{S2} \) are very improbable, the \( N \) diodes \( D_n \) anyway allow to correctly route the current through the inductor L.
Fig. 5: Experimental results of the realized parallel-like power management circuit of Fig. 3 (N = 2). $v_{CS1}$ and $v_{CS2}$ voltages across the 22-$\mu$F transfer storage capacitors $C_{S1}$, $C_{S2}$, $v_{CSout}$ voltage across the 100-$\mu$F storage $C_{Sout}$, $v_L$ voltage across the 100-mH inductor $L$, $V_{TH}$ and $V_{TL}$ thresholds of the trigger circuits TC$_1$ and TC$_2$ (a). When TC$_1$ toggles, the energy stored in $C_{S1}$ is transferred to $C_{Sout}$ (b).

4. Conclusions

In this paper, innovative power management circuits for multi-source piezoelectric energy harvesting systems which exploit custom trigger circuits to avoid the limitations of traditional topologies were presented. The electronic devices within the power management circuits are directly powered by the energy converters, thus neither dedicated start-up circuits nor external power supplies are required, and the systems are entirely battery-less.

In the proposed series-like power management circuit, each storage capacitor is individually charged by its own energy converter. All the storage capacitors are connected in series and power the load by providing a supply voltage given by the sum of their voltage levels. If the energy levels of the storage capacitors are different, the power management circuit prevents the capacitor with the highest energy level to reverse charge the other capacitors.

The proposed parallel-like power management circuit independently extracts power from each converter by charging separate transfer capacitors. Subsequently, the energy from each transfer capacitor is conveyed into a single output storage capacitor through an inverting buck-boost power stage. In this way the power from each converter charges the output storage capacitor regardless of its voltage level.

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