A bidirectional energy conversion circuit for piezoelectric energy harvesting and vibration exciting purposes

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ABSTRACT

Piezoelectric transducers provide a bidirectional channel for converting energy from mechanical form to electrical or in the opposite direction. Various applications were developed according to either of these two energy-flow processes. For example, energy harvesters take advantage of the energy flow from mechanical to electrical domains, while vibration exciters take advantage of that from electrical to mechanical domains. Few of the former designs have integrated the bidirectional energy-flow processes in a single device. Nevertheless, such integration can be very useful in some application scenarios. The key obstacle results from the interface circuit design, rather than the transducer. This paper makes a breakthrough by proposing a bidirectional energy conversion circuit (BECC) solution for the time-dividing energy harvesting and vibration exciting purposes. The circuit topology is derived from the synchronized triple bias-flip circuit, which was formerly used for the energy harvesting enhancement. The control logic for energy harvesting and vibration exciting modes are discussed in details. Two piezoelectric designs are studied for investigating the potential applications of BECC. For the linear piezoelectric structure, the BECC can be used to provide vibration excitation and then reclaim a part of the injected energy. The proposed BECC can be also used to realize the controllable high-energy orbit exciter in the nonlinear piezoelectric energy harvesting systems. It is the first time to realize a compact and integrated self-excitable nonlinear energy harvester by using a single interface circuit. Simulations and experiments are carried out for validating the performance of the BECC towards future engineering designs.

Keywords: piezoelectric energy harvesting, bidirectional energy conversion circuit, high-energy orbit, nonlinear oscillator

1. INTRODUCTION

Piezoelectric materials have been utilized in many engineering applications since the discovery of piezoelectricity in 1880.¹ The piezoelectricity is summarized by two effects, say, the direct piezoelectric effect, with which the electrical variable changes according to the variation of the mechanical variable, and the inverse piezoelectric effect, with which mechanical variable changes according to the variation of the electrical variable. The direct and inverse piezoelectric effects coexist in the general piezoelectric operations. Given the versatile features of the piezoelectric materials, they have been made into many useful engineering designs, such as the vibration sensors, micro-positioning actuators, etc. The term “sensor” is more referred to the device converting the physical variable into the electrical signal, while “actuator” is referred to the device producing specific mechanical movement according to the electrical input. Literally speaking, the energy flow direction is not specified in these two kinds of devices.

On the other hand, given the conservation of energy, a piezoelectric transducer, which provides a channel for energy transformation, can either convert energy from mechanical form to electrical or in the opposite direction. These two energy-flow processes are mutually exclusive and cannot happen at the same time. In terms of the direction of net energy flow, the energy harvesters extract energy from mechanical to electrical domains, while the vibration exciters inject energy from electrical to mechanical domains. Given the mutual exclusion of the
two energy-flow processes, the former designs of energy harvesters and vibration exciters have little crossover. Recently, there are some applications summoning the integration of the two energy-flow processes towards the compact and robust piezoelectric system designs. The idea is not to violate the conservation of energy, which is impossible, but to implement either of the two energy-flow processes in specific and separated time intervals, which is referred to as the time-dividing operations. For example, in some nondestructive evaluation (NDE) cases, a piezoelectric device should act as a vibration exciter at the beginning and then change into a sensor for signal detection. Besides, in some nonlinear energy harvester solutions, vibration excitation is needed for some period, in order to drive the harvester onto the high-energy vibration orbit. In the previous designs, people realize both the vibration excitation and energy harvesting functions by simply combining two separated units.\textsuperscript{2,3} Either function runs while the other is deactivated. Such simple combinations are not smart and robust enough towards sophisticated mechatronic designs. The problem can be solved by introducing the new organic designs, which enable the time-dividing bidirectional energy flow through the electromechanical transduction channel.

The difficulty of realizing the bidirectional energy conversion is not caused by the piezoelectric transducer, but the interface circuit. Nevertheless, former vibration exciter designs have only considered the electrical-to-mechanical energy conversion, while the energy harvester designs have only considered the other way round until the proposals of the “active energy harvesting” schemes.\textsuperscript{4–7} In those designs, by properly producing energy injection from electrical to mechanical domains, the energy harvesting capability of the overall system has been enhanced. The electrical to mechanical energy injection was implemented in a very short interval during each vibration cycle; it was not singled out for realizing the vibration excitation in those energy harvesting designs.

The investigation on bidirectional energy conversion circuit (BECC) starts from a recently proposed energy-investing harvesting circuit, the synchronized triple bias-flip (S3BF) circuit.\textsuperscript{7,8} By using the same circuit topology but carrying out different switching control sequences, the time-dividing energy harvesting and vibration excitation functions are realized by using a single interface circuit. Such an integrated design may lead to the inventions of many effective solutions for vibration-powered NDE devices\textsuperscript{9} and nonlinear energy harvesters.\textsuperscript{10}

2. CIRCUIT TOPOLOGY AND OPERATIONS

The synchronized switch harvesting on inductor (SSHI) technologies was developed around 2005,\textsuperscript{11} which was utilized for improving the power factor with efficient power electronics. The bias-flip actions in SSHI are all passive, i.e., energy is only extracted from the piezoelectric structure. The active bias-flip actions, i.e., energy is injected to the piezoelectric structure, were introduced in the later technologies called “energy investment”,\textsuperscript{5} “energy injection”,\textsuperscript{6} etc. In those designs, the active bias-flip actions are inserted in specific phases of each cycle for increasing the net harvested power. The general model of synchronized multiple bias-flip (SMBF) and two derived implementations S3BF (\(M = 3\)) and STBF (\(M = 3\)) were proposed and analyzed by Liang et al.\textsuperscript{12,13} To further eliminate the passive components and make the circuit simpler, Zhao et al.\textsuperscript{8} have removed the bridge rectifier in the parallel path and managed to integrate the bias source and energy storage into one single capacitor. The new circuit topology is called the series-S3BF (S-S3BF). With the S-S3BF topology, more functions besides energy harvesting can be realized by sophisticatedly scheduling the passive and active bias-flip actions. The BECC scheme investigated in this paper is implemented by applying different control sequences on such S-S3BF topology.

The equivalent circuit of a linear piezoelectric structure connected to the S-S3BF BECC is shown in Fig. 1(a). The piezoelectric structure has the following dynamic components: the equivalent voltage source \(v_\text{eq}(t)\), which is proportional to the applied excitation force; the resonant tank formed by \(R, L, \) and \(C\), which are equivalents of the mechanical damping, mass, and stiffness, respectively; the piezoelectric clamped capacitance \(C_p\); and the shunt leakage resistance \(R_p\). \(i_\text{eq}(t)\) the current flowing through the \(RLC\) circuit is proportional to the vibration velocity. The S-S3BF BECC is realized by a current-steering H-bridge like switch network configuration. The switch network is composed of eight power MOSFET and four diodes for strictly controlling the current flow direction in each bias-flip action. In each cell of switches, i.e., from \(M_x1\) to \(M_x4\) (\(x = 0, 1\)), the two transistors \(M_x1\) and \(M_x2\) form a bidirectional switch; \(M_x3\) and \(D_x3\) form the upward current path; and \(M_x4\) and \(D_x4\) form the downward one. The capacitor \(C_b\) connects the middle points of the two switch branches. The forward or backward connected \(C_b\) provides voltage references for the bias-flip actions. It absorbs energy in energy harvesting mode, while supplies energy in the vibration exciting mode.
Figure 1. BECC circuit topology and operation waveforms. (a) Equivalent circuit of a linear piezoelectric structure using the S-S3BF BECC. (b) Voltage and current in the energy harvesting mode with their enlarged view in (c). (d) Voltage and current in the vibration exciting mode with their enlarged view in (e).

Table 1. Summary of six bias-flip actions.

<table>
<thead>
<tr>
<th>Action code</th>
<th>Bias voltage</th>
<th>Flipping direction</th>
<th>Conducting MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{p1, dn}</td>
<td>V_b</td>
<td>downstairs</td>
<td>M_{11}, M_{12}, M_{04}</td>
</tr>
<tr>
<td>P_{0, dn}</td>
<td>0</td>
<td>downstairs</td>
<td>M_{01}, M_{02}, M_{04}</td>
</tr>
<tr>
<td>P_{n1, dn}</td>
<td>-V_b</td>
<td>downstairs</td>
<td>M_{01}, M_{02}, M_{14}</td>
</tr>
<tr>
<td>P_{p1, up}</td>
<td>V_b</td>
<td>upstairs</td>
<td>M_{11}, M_{12}, M_{03}</td>
</tr>
<tr>
<td>P_{0, up}</td>
<td>0</td>
<td>upstairs</td>
<td>M_{01}, M_{02}, M_{03}</td>
</tr>
<tr>
<td>P_{n1, up}</td>
<td>-V_b</td>
<td>upstairs</td>
<td>M_{01}, M_{02}, M_{13}</td>
</tr>
</tbody>
</table>

Table 2. Switch controls of BECC under different operation modes.

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>Bias-flip actions sequence at voltage maxima</th>
<th>Bias-flip actions sequence at voltage minima</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1BF energy harvesting</td>
<td>P_{p1, dn} \rightarrow P_{0, dn} \rightarrow P_{n1, dn}</td>
<td>P_{n1, up} \rightarrow P_{0, up} \rightarrow P_{p1, up}</td>
</tr>
<tr>
<td>S3BF energy harvesting</td>
<td>P_{n1, dn} \rightarrow P_{p1, up} \rightarrow P_{n1, dn}</td>
<td>P_{p1, up} \rightarrow P_{n1, dn} \rightarrow P_{p1, up}</td>
</tr>
</tbody>
</table>

Table 1 summarizes the six bias-flip actions, which are able to be carried out with the S-S3BF topology. The first subscript in the action code denotes the polarity and multiple of the bias-voltage, say, “p1” means positive one times V_b while “n1” means −V_b. The second subscript denotes the voltage flipping direction, say “dn” for downstairs flipping and “up” for upstairs flipping. The six actions are basic ingredients towards varies...
Figure 2. Time evolutions of a linear piezoelectric structure under the vibration exciting and then energy harvesting operations with the S-S3BF BECC (red curves denotes the vibration exciting mode while blue denotes the energy harvesting mode). (a) and (b) S1BF vibration exciting and then S1BF energy harvesting modes. (c) and (d) S3BF vibration exciting and then S1BF energy harvesting modes.

operations. For example, as shown in Table 2, the four operation modes used in this study for either energy harvesting or vibration exciting purposes are derived from some permutations and combinations out of the six actions.

3. APPLICATION IN A LINEAR PIEZOELECTRIC SYSTEM

A piezoelectric system integrated with a linear mechanical structure and the BECC interface circuit is implemented and simulated for validating the idea of bidirectional energy conversion under different control logic. The parameters of the linear piezoelectric structure are indirectly obtained from the practical setup based on the following formulas under the first flexural mode excitation.

\[
\alpha_e = \beta C_p, \quad K = \alpha_e \beta \frac{f_{sc}^2}{f_{oc}^2 - f_{sc}^2}, \quad M = \frac{K}{4\pi^2 f_{sc}^2}, \quad D = 4\pi \zeta M f_{oc},
\]

where \( \alpha_e \) is the force-voltage factor, which equals to 0.00013 N/V in the experimental beam; the mass \( M = 8.2 \) g; damping \( D = 0.009 \) N/(m/s); stiffness \( K = 48.2 \) N/m; \( f_{sc} \) is the short-circuit resonant frequency; \( f_{oc} \) is the open-circuit resonant frequency, \( \zeta \) is the damping ratio under open-circuit condition; and \( \beta \) represents the ratio between open-circuit voltage to the beam free-end deflection.

Fig. 2 gives the simulation results based on the aforementioned set of parameters. The system enters the vibration exciting mode from zero velocity and displacement. The storage capacitor \( C_b \), whose capacitance is 100 \( \mu \)F is pre-charged to 30 V initial voltage. During the vibration excitation, the beam velocity and displacement magnitudes gradually get larger, as shown by the red segments. The energy in \( C_b \) is transformed into mechanical energy associating with the beam vibration. After 0.75-second of vibration excitation, the BECC is switched to the energy harvesting mode. The mechanical energy is transformed back into electrical form through the S-SSH1 scheme. As we can see from Fig. 2(b), the beam vibration quickly damps out in the energy harvesting...
mode (blue segment), because energy harvesting can electrically induce additional damping to the mechanical structure. The BECC operations are successfully validated through this example.

The more powerful excitation can be achieved by carrying out more times of bias-flip actions. For example, by taking the S3BF vibration exciting mode as listed in Table 2, the energy injection from $C_b$ to the piezoelectric structures repeats three times in each synchronized instant, making larger $v_p$ magnitude across the piezoelectric transducer. Compared to the results using S1BF excitation, which are shown in Fig. 2(a) and (b), Fig. 2(c) and (d) illustrate that the vibration level by using the S3BF excitation is higher than that using S1BF excitation. Since the S3BF scheme has injected more energy into the system, after 0.75-second, when the BECC is switched to the energy harvesting mode, the vibration damps out slower than the former case with the same S1BF energy harvesting control.

The linear structure using BECC shows a basic example of time-dividing vibration excitation and energy harvesting. A more significant application would be made by realizing the organically integrated high-energy orbit (HEO) exciter and energy harvester for the first time in nonlinear energy harvesters.

### 4. APPLICATION IN A NONLINEAR PEH SYSTEM

To expand the bandwidth of the vibration response, nonlinear terms are brought into the mechanical part of a piezoelectric energy harvesting (PEH) system, mainly through magnetic forces and buckling forces.\(^{14,15}\) According to the different numbers and forms of the nonlinear terms, the system can be characterized to be monostable,\(^{16}\) bistable,\(^{17}\) tristable,\(^{18}\) etc. One common feature shared by different nonlinear systems is that multiple limit cycles coexist in some frequency spans. The multi-limit-cycle feature makes the nonlinear energy harvesters more popular over their linear counterparts, in terms of broader bandwidth and higher power output level.\(^{15}\) To take advantage of such multi-limit-cycle feature, we have to first overcome the challenge about how to arrive at the limit cycle associating with the largest vibration magnitude. This challenge has attracted much research effort for making good use of all limit cycle oscillations towards the energy harvesting purpose.\(^{10}\) In this study, we use the proposed BECC to offer an integrated solution for both energy harvesting and vibration excitation from low- to high-energy orbit, i.e., the transfer from small magnitude limit cycle to larger magnitude one.

The designed monostable piezoelectric energy harvester is shown in Fig. 3. Two magnets are used to introduce the nonlinear repelling force, one fixed on the base and the other at the free end of the cantilevered beam. Tuning the distance between the two magnets, a monostable system can be achieved. The piezoelectric patch is connected to the BECC interface circuit and to the energy storage. The conceptual control procedures of the multi-functional BECC are explained as follows: (1) At the beginning, the monostable system stays on the low-energy orbit with a small vibration amplitude. The system works under energy harvesting mode and stores the energy in the electrical energy storage; (2) The vibration exciting mode is activated to inject energy from the storage to the transducer. The vibration of the system begins to be amplified; (3) After the system reaches HEO, the BECC is switched back to energy harvesting mode. The monostable energy harvester now maintains...
on the HEO and collects energy much faster, i.e., has a higher harvested power, then before at the low-energy orbit.

To validate the BECC control method, a nonlinear energy harvester model is developed in Simulink for investigating the dynamics. The nonlinear structure exhibits different frequency responses when undergoing upward or downward frequency scanning. Applying the frequency sweeping excitation from 5 to 10 Hz (upward scanning) or from 10 to 5 Hz (downward scanning) with a constant excitation amplitude of 1.38 m/s², Fig. 4 shows the two corresponding mechanical responses in red and blue curves, respectively. Two jumps are observed at different frequencies in the scanning results. The hysteresis region is defined in the frequency span between the two jumps. Within the region, the nonlinear harvester may attain steady-state vibration at either the low- or high-energy tracks. For the sake of harnessing more energy from the same mechanical vibration, the red solutions, i.e. the one at HEO, is preferable.

After knowing about the hysteresis region around 7 to 8 Hz, a 7.4 Hz harmonic base excitation is applied to the experimental cantilevered structure. Fig. 5 shows the dynamic evolution of the experimental vibrator under the BECC control. In the beginning, the structure vibrates on the low-energy track, which is illustrated

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**Figure 4. Frequency sweep tests.**

**Figure 5. Energy harvesting and orbit jump in nonlinear PEH experiment by using BECC.**
by the blue segment from 0 to 2.6-sec. The transformed energy is collected from small amplitude vibration at a relatively slow rate. At 2.6-sec, the BECC is switched to the vibration exciting mode. The energy stored in the storage capacitor $C_b$ is now released and pumped back to energize the structure. The displacement and velocity of the oscillator gradually increase and reach the HEO after several cycles (middle segment in red). At this point, the BECC is switched back to the energy harvesting mode at 10.3-sec. The oscillator now works under the HEO and offers a much higher voltage output (right segment in blue). Comparing the two blue curves before and after the orbit jump, the vibration magnitude has been amplified for over 3 times. The experiments validated that the BECC is useful for offering an integrated HEO excitation and energy harvesting solutions for the nonlinear PEH systems.

5. CONCLUSION

A new circuit solution was introduced in this paper for the efficient bidirectional energy conversion in piezoelectric devices. For the first time, it offers an integrated solution for both energy harvesting and vibration exciting purposes. The circuit topology of its control schemes towards different working modes was explained in details. The operations with two different excitation intensities were validated with a linear piezoelectric model in Simulink. One of the potential application scenarios of this bidirectional energy conversion circuit (BECC) is the nonlinear energy harvesting system. We have also offered an initial case study of utilizing the BECC towards the realization of controllable orbit jump in a monostable system. Within the hysteresis frequency range, besides fulfilling the energy harvesting function, the BECC can also excite the piezoelectric structure from the initial smaller vibration along the low-energy orbit to the larger vibration along the high-energy orbit. Experiments have demonstrated the effective performance of the BECC power conditioning piezoelectric systems. The future work will focus on the further improvement of the BECC control as well as the more understanding on the detailed workable range of the BECC in nonlinear energy harvesting.

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