Proceedings of the ASME 2019
International Design Engineering Technical Conferences
and Computers and Information in Engineering Conference
IDETC/CIE2019
August 18-21, 2019, Anaheim, CA, USA

DETC2019-97807

ORBIT JUMPS OF MONOSTABLE ENERGY HARVESTERS BY A BIDIRECTIONAL ENERGY CONVERSION CIRCUIT

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ABSTRACT
Nonlinear energy harvesters have been widely studied in the last decade. Their broad bandwidth and relatively high power output contribute to energy harvesting applications. However, the coexisting multiple orbits brought by the nonlinearity weaken the performance of nonlinear energy harvesters. This paper proposes to achieve orbit jumps of monostable energy harvesters by a bidirectional energy conversion circuit. Changing the switch control sequence in the bidirectional energy conversion circuit facilitates it with both the energy harvesting and vibration exciting functions. Thus, a nonlinear energy harvester in connection with the circuit can harness ambient energy as well as excite itself, through energy harvesting and vibration exciting modes separately. Based on the concept of vibration exciting, the energy saved in the storage is used to stimulate the piezoelectric transducer for a larger vibration amplitude, which enables orbit jumps. The working mechanism of the circuit is introduced. Experimental setup of a monostable energy harvester has been developed to validate the proposed method. The monostable system can be stimulated to high-energy orbit from a small vibration amplitude by the vibration exciting mode of the circuit. It is also revealed that the method can achieve orbit jumps in a wide frequency range within the hysteresis area. Evaluations on energy consumption and energy gain show that the sacrificed energy can be quickly recovered. A novel approach for orbit jumps of monostable energy harvesters is performed so as to open new opportunities for monostable energy harvesters.

Keywords: monostable energy harvester, orbit jump, high-energy orbit, bidirectional energy conversion circuit

1. INTRODUCTION
On the road towards IoT (Internet of Things) era, work and life become convenient and fast. All distributed sensors and processing nodes, as a critical section in IoT, rely on cabled power sources or batteries, which encounters difficulties of limited size requirements and battery maintenance. To address this issue, energy harvesting, with decades' developments, is regarded as a solid solution. Energy harvesting technologies collect energy from the ambience and convert it into useful electricity. They enable the future IoT devices to become self-sustainable. Specific strategies can vary according to different application scenarios and requirements [1]. Among various technologies, vibrational energy harvesters are popular due to the abundance of vibration in surroundings. Past efforts have been paid on increasing the resonant power output of energy harvesters from mechanical [2] and electrical [3] avenues. However, the studied linear system is not robust to parameter variations, which undermines its feasibility and performance. Nonlinear energy harvesters are now deemed as a promising potential in terms of power level and bandwidth.

Intentionally introducing strong nonlinearity into the linear system creates a nonlinear system, which destabilizes the original only stable state to bifurcate to two or more limit cycles or even chaos. At the same time, the system turns out to be sensitive to external disturbance. The nonlinear energy harvester, benefiting from the nonlinear hardening or softening effects, possesses a broader bandwidth and larger power output in some range, compared with its linear counterpart. However, among the different oscillating states, only the largest periodic orbit, named high-energy orbit (HEO) hereafter, is favorable for energy harvesting purposes. Therefore, orbit jumps are essential for the nonlinear energy harvester as the system is not settling on HEO.

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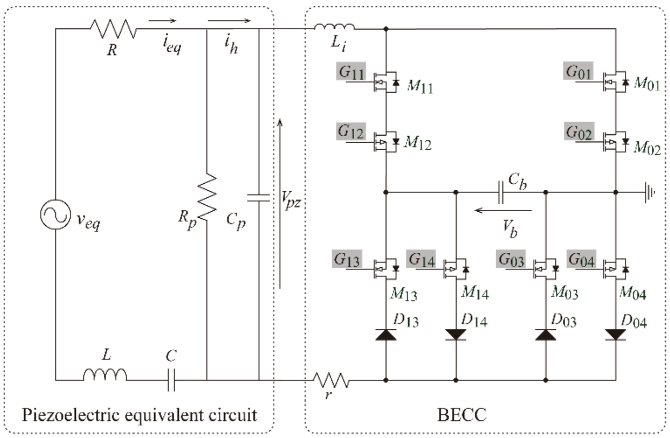

FIGURE 1: PIEZOELECTRIC ENERGY HARVESTER WITH THE BECC CIRCUIT.

In literature, different methods have been employed to realize orbit jumps. By means of the high sensitivity of nonlinear systems, some researchers focus on the disturbance strategy that a sudden interference may force the system to change its states. Su at al. [4] momentarily altered the system's damping through an electromagnetic restraining device. A phase shift in the excitation was also revealed to produce orbit jumps for a bistable energy harvester [5]. These economic approaches highly rely on the system's abilities. In other words, the capability of these semi-active methods is limited. On the other hand, some researchers employ active methods by injecting energy to inspire orbit jumps. Mechanical impact [6,7] was used by a hand or projectile to activate the system to HEO. It also brings a disturbance into the system, but the injected energy by impact primarily accounts for the success of orbit jumps. A direct brief high voltage input on the piezoelectric [8] or electromagnetic [9] transducers also pushed the system to go higher and reach the HEO. Or indirectly, the energy injection could be finished by a negative impedance converter to achieve orbit jumps [10,11]. For these active methods, an intense energy injection, usually fulfilled by an external power supply, is required, which is against the intention of energy harvesting. In this paper, one active and practical approach for orbit jumps of monostable energy harvesters is proposed based on a bidirectional energy conversion circuit (BECC).

The paper organizes as follows. After the introduction, the working mechanism of the BECC is briefly explained. Section 3 presents the working principle of the proposed method and the experimental results of orbit jumps using the BECC. Multiple trials have been carried out over a frequency span to demonstrate the capability of the approach. The energy consumption and gain are studied in Section 4 to evaluate the approach. Finally, Section 5 draws the conclusions.

2. WORKING MECHANISM

A detailed introduction of the BECC has been presented in [12]. A brief explanation is given below. Based on the synchronized multiple bias-flip (SMBF) energy harvesting

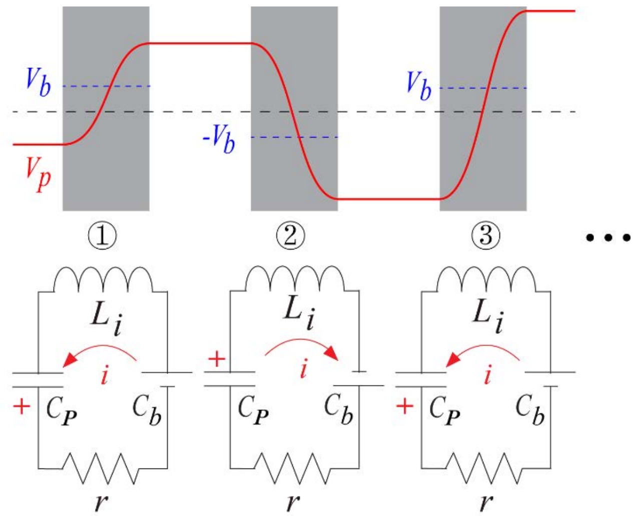

FIGURE 2: VIBRATION EXCITING AT UPSTAIRS AND ITS EQUIVALENT CIRCUIT. ODD NUMBERS DENOTE POSITIVE CHARGING WHILE EVEN NUNBERS REPRESENT THE NEGATIVE CHARGING PROCESS. THREE CONSECUTIVE CHARGING PROCESSES ARE SHOWN HERE, MORE ACTIONS CAN BE ADDED AT EACH PIEZOELECTRIC VOLTAGE EXTREME.

circuit as shown in FIGURE 1, changing the switch control sequence, the original energy harvesting circuit can work under a vibration exciting mode, which allows energy in the storage return to the transducer. The eight power MOSFET, controlled by a microcontroller unit (MSP430 F2274), are used as switches for realizing different control sequences. Four diodes steer the currents for the self-adaptive feature of the circuit [13]. The bias capacitor C_b functions as both the energy storage and bias source.

Since the energy harvesting function of the BECC is same as that in the SMBF circuit which has been repeatedly discussed, this section emphasizes on the vibration exciting mode. At each instant of the piezoelectric voltage extreme, neglecting the shunt leakage resistance R_p, the vibration exciting process can be presented as a charging action on the clamped capacitance C_p with storage C_b. C_b, with a relatively large capacitance, is regarded as a stable power source. It charges C_p through an LCR oscillation formed by an inductor L_i, C_p and the parasitic resistor r, thus the process is denoted as energy injection. Different connections of C_p of C_b result in the so-called positive charging or negative charging according to the charging current direction, shown in FIGURE 2. Through charging the electrical energy will be transferred to mechanical energy by the transducer. Therefore, a vibration exciting function is realized. By multiple successive charging actions at every voltage extreme of C_p, a theoretical infinite high voltage can be obtained. To ensure the stimulating function, an odd number must be set for the charging action in each piezoelectric voltage extreme. Or, same directional charges on the transducer as its original polarity will oppose the harvester's motion.

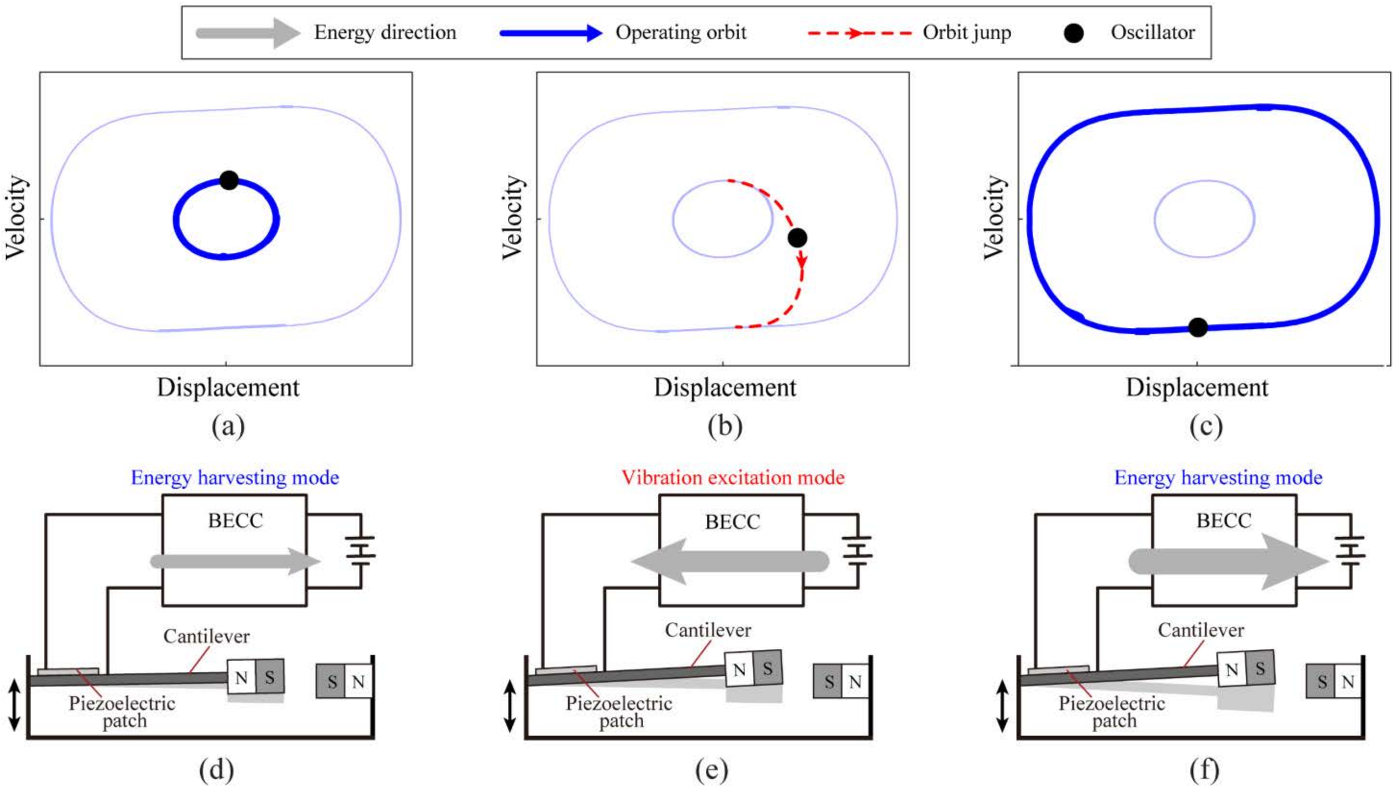

FIGURE 3: ENERGY HARVESTING AND ORBIT JUMP REALIZED BY THE BECC. (a) AND (d) INITIAL ENERGY HARVESTING MODE AT LOW-ENERGY ORBIT. (b) AND (e) VIBRATION EXCITING MODE FOR ORBIT JUMP. (c) AND (f) ENERGY HARVESTING MODE AT HIGH-ENERGY ORBIT.

3. ORBIT JUMPS

3.1 Working principal

For a stronger capability, energy injection concept is adopted in this work. By actively giving energy saved in the storage to the piezoelectric transducer, the transducer is excited to a larger vibration, which is accompanied by the vibration exciting mode of the BECC as explained in Section 2. An ideal source can create an infinite large voltage by infinite charging actions at each piezoelectric voltage extreme. However, considering that the energy in storage C_b is confined, a three bias-flip charging at each piezoelectric voltage extreme is chosen for the orbit jump.

FIGURE 3 shows the working principle of orbit jumps for a piezoelectric energy harvester system in detail. The nonlinearity is introduced by two repelling cubic magnets, one installed on the base frame and the other at the free end of the cantilevered beam. A monostable system can be achieved by tuning the distance between the two magnets. The electrodes of the piezoelectric patch are connected to the BECC interface circuit. The nonlinear system starts to vibrate at the low-energy orbit; the BECC absorbs energy and stores it in the electrical storage, as illustrated in FIGURE 3(a) and (d). When the stored energy is accumulated above a specific level, the vibration exciting mode is activated to destabilize the vibration at low-energy orbit by electrical-to-mechanical energy injection, to push the oscillator to cross the energy barrier and jump onto the HEO, as illustrated in FIGURE 3(b) and (e). When the orbit transformation is done, the BECC is switched back to the energy harvesting mode and the system enjoys a higher harvesting power under the vibration at HEO, as illustrated in Fig. 3(c) and (f).

3.2 Orbit jumps in experiments

In experiments, the monostable energy harvester is excited by a vibrating system (SPEKTRA APS420). A vibrometer (Polytec OFV-552/5000) tracks the beam end displacement and velocity. The voltages of the storage and piezoelectric transducer are recorded by an oscilloscope (TELEDYNE HDO6104A). A constant amplitude excitation with linearly increasing and decreasing frequency is firstly added on the energy harvester. The displacement amplitude of the energy harvester experiences sharp jumps in each frequency sweep test, as shown in FIGURE 4. For the upward sweep results shown by the red curve, the amplitude increases along the sweep direction. But at 8.3 Hz, the system drops suddenly to a much lower amplitude track, as the red arrow shows. Then the system's motion gradually shrinks along the sweep direction. A similar trend is also observed during the downward sweep test,

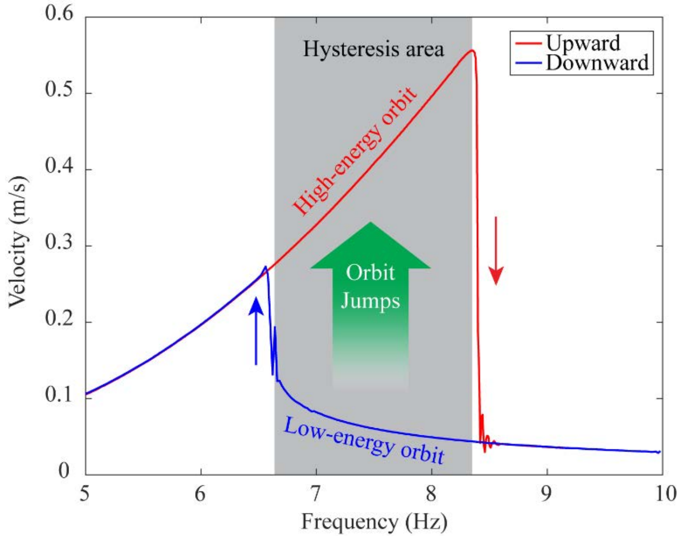

FIGURE 4: FREQUENCY SWEEP TEST RESULTS. GRAY REGION SHOWS THE HYSTERESIS AREA. WITHIN THE HYSTERESIS AREA, LOW ENERGY ORBIT AND HIGH-ENERGY ORBIT COEXIST. ACTIONS FROM LOW-ENERGY ORBIT TO HIGH-ENERGY ORBIT IS CALLED ORBIT JUMPS AS THE GREEN ARROW SHOWS.

while the system picks a sharp rise at 6.7 Hz shown by the blue arrow. Within these two jumps, the multi-solution region is defined as the hysteresis area, where the system can stay on either of the two orbits determined by initial conditions and excitation status. Once the system is on the low-energy orbit, the vibration exciting mode of the BECC will be used to trigger orbit jumps for high energy output.

One experimental orbit jump under 7.6 Hz sinusoidal excitation is shown in FIGURE 5. Initially, the BECC works under energy harvesting mode and the system possesses a small vibration amplitude, which is displayed by the first blue segment. At 1.7 s, the BECC is switched to vibration exciting mode and it lets electrical energy flows to the transducer. Thus, a larger mechanical displacement is obtained through the transduction of the transducer. From the phase portrait, at the end of the vibration exciting process shown by the red segment, the system's amplitude has reached beyond the HEO. At 12.6 s, the BECC is switched back to energy harvesting mode. The system remains on HEO and harnesses energy much faster than that before the energy injection, as the second blue segment shows. A 10.9-second vibration exciting with a certain amount of energy injection has realized the orbit jump for the monostable system. To assess the capability of the approached method, multiple tests have been carried out under different frequencies within the hysteresis area. It is revealed that the orbit jumps can be achieved under excitations from 7.0 Hz to 7.6 Hz, which ensures high feasibility of the proposed method. The quantitative energy consumption and energy gain will be investigated in the next section.

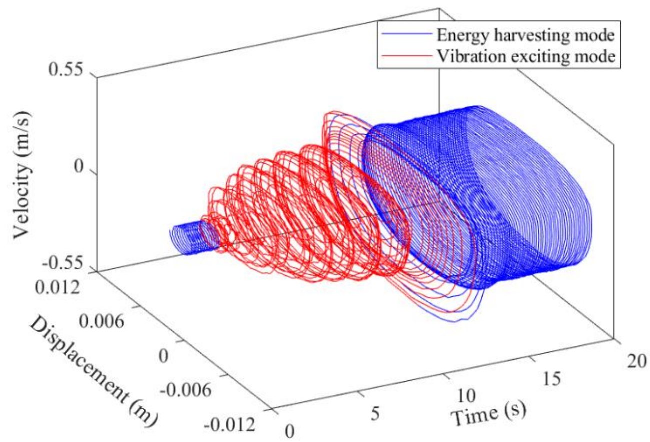

FIGURE 5: SYSTEM TRAJECTORY OF THE ORBIT JUMP.

4. ENERGY ANALYSIS

It has been shown that the proposed approach indeed inspires orbit jumps of the monostable energy harvester. The quantitative evaluation of the approach performance, i.e., the payment and outcome, is conducted in this section. The payment defines energy consumed for the orbit jumps, which consists of microcontroller unit powering, switch operations and energy injected to the transducer. As for the energy gain, it is the increased energy by HEO energy harvesting compared with the energy before orbit jumps. Focusing on the energy flow within the energy harvester, the energy used on the microcontroller unit is neglected. As for the switches, the power consumption is approximated to be around μW level considering the operation range of the monostable energy harvester [13]. The power consumption on the switches is trivial compared to the energy harvesting power on HEO, which will be shown later. Therefore, the energy used for vibration exciting is a major expenditure. Measuring the voltage level, the consumed energy is formulated as

$$E_{VE} = \frac{1}{2} \times C_b \times \left(V_{bf}^2 - V_{aft}^2\right) \approx 22\text{mJ} \tag{1}$$

where V_{bf}, V_{aft} represent the voltage before and after the vibration exciting action.

As for the outcome, the system energy gain is tracked on low- and high-energy orbits, shown in FIGURE 6. The piezoelectric voltage has been raised for about three times from low-energy orbit to HEO shown by red curves. On the other hand, it is shown by the blue curves that a sharp slope of the capacitor voltage is achieved after the orbit jumps. This indicates that the energy harvesting power has been increased, more specifically for 9.4 times from measurements. With an average harvesting power of 0.2 mW at HEO, the consumed energy E_{VE} can be recovered about 2 min. The energy analysis implies that the proposed approach for orbit jumps is potential for a self-sustaining nonlinear energy harvesting system.

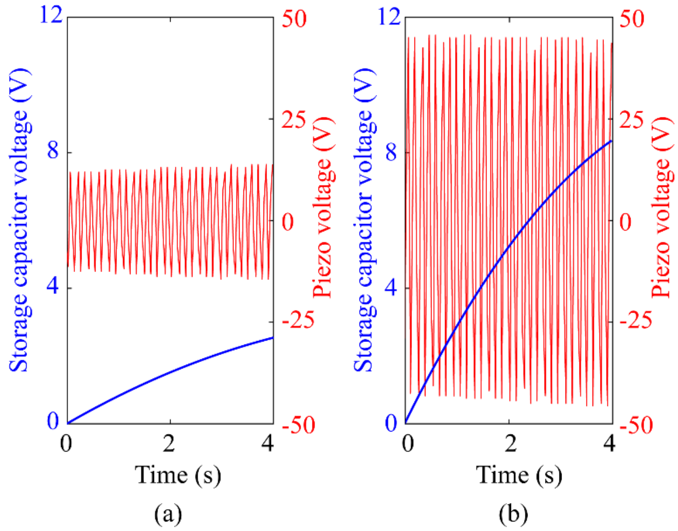

FIGURE 6: STORAGE CAPACITOR VOLTAGE AND PIEZOELECTRIC VOLTAGE UNDER ENERGY HARVESTING. (a) THE SYSTEM IS ON THE LOW-ENERGY ORBIT AND (b) The SYSTEM ON HIGH-ENERGY ORBIT.

5. CONCLUSIONS

In this paper, an approach based on a bidirectional energy conversion circuit for orbit jumps of monostable energy harvesters is performed. The working mechanism of the circuit shows that vibration exciting function is obtained through different switch control sequences. The vibration exciting mode enables energy injection from the storage to the transducer; thus, a larger vibration can be achieved. Details about the orbit jumps are explained in the working principle of orbit jumps. One monostable energy harvester is developed to validate the proposed approach. The results show that orbit jumps can be accomplished over a wide frequency span within the hysteresis area. Energy analysis deals with energy consumption for the orbit jumps and energy gain. The output power of the monostable energy harvester on HEO has been increased for 9.4 times. Under this power, the sacrificed energy can be quickly recovered. Therefore, the proposed method can use its own energy to realize the orbit jumps, which may lead to the practical application for monostable energy harvesters. In the future, system parameters will be optimized, targeting a higher power output.

ACKNOWLEDGEMENTS

The work described in this paper was supported by the grants from Research Grants Council of Hong Kong Special Administrative Region, China (Project No. CUHK 14205917), National Natural Science Foundation of China (Project No. 61401277), and ShanghaiTech University (Project No. F-0203-13-003). The support for Mr. Jiahua Wang provided by Research Grants Council under Hong Kong PhD Fellowship Scheme is also acknowledged.

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