ICAST2014 #014

Synchronized Triple Bias-Flips Harvesting Circuit: A New Solution for Piezoelectric Energy Harvesting Enhancement

Junrui Liang

School of Information Science and Technology, ShanghaiTech University, Shanghai, China

Abstract

The energy harvesting capability of piezoelectric energy harvesting (PEH) systems can be significantly enhanced by adopting synchronized switching interface circuits, e.g., the synchronized switch harvesting on inductor (SSHI). On the other hand, recent circuit advancements have shown that, by sophisticatedly injecting energy into the vibrating system at some proper instants, the harvesting capability can be further boosted. The combination of energy harvesting steps, which are generally passive bias-flip actions, and auxiliary energy injection steps, which are active bias-flip actions, has introduced a more complicated energy flowing scenario across the electromechanical interface. A best voltage bias-flip strategy was developed for generalizing the optimal timing and strength of each bias-flip action towards an overall outcome of maximum harvested power. Based on the theoretical guidance of the best bias-flip strategy and a compromise between the effectiveness of improvement and the complexity of implementation, a new interface circuit called parallel synchronized triple bias-flips (P-S3BF) is proposed in this paper. The P-S3BF scheme makes the full use of an auxiliary bias voltage source for exerting appropriate bias-flip actions in time; therefore outperforms other configurations using single auxiliary bias source. Some detailed circuit mechanisms are embodied in the proposed P-S3BF topology for ensuring the stability of the PEH system. Simulation results verify the theoretical derivation and provide reference for the ongoing circuit implementation.

1. INTRODUCTION

The ambient energy harvesting technologies have attracted extensive research efforts during the last decade, with the purpose to convert the dispersive energy in our surrounding into useful electricity, and someday realize the power self-sufficiency of distributed and mobile electronics. Piezoelectricity provides one of the most popular transduction mechanisms for extracting useful electric power from the ambient vibration sources. In the studies of piezoelectric energy harvesting (PEH), various solutions have been developed for broadening the bandwidth of energy transfer from the vibration source to mechanical structure [1, 2] and/or enhancing the energy transduction from the mechanical structure to electrical circuit [3]. According to the literature, the bandwidth broadening can be more effectively achieved by mechanical methods, such as adopting bistable mechanical structures [2]; on the other hand, the record of harvesting capability under the same mechanical condition has been refreshed time after time as a result of continuous circuit improvement [3, 4].

The synchronized switch harvesting on inductor (SSHI) interface circuit can enhance the harvesting capability by up to several hundred percent [4-6], and therefore has set a significant milestone in the evolution of PEH circuits. In SSHI, including its series and parallel versions, the piezoelectric voltage is

---

[1] Email: liangjr@shanghaitech.edu.cn

flipped over for once with respect to a bias voltage at each velocity zero-crossing; the bias-flip actions in SSHI are all passive, i.e., the bias source always absorbs rather than provides energy to the system. After SSHI, some solutions emerged and it was claimed that the harvested capability can be further enhanced by taking active intervention, i.e., pumping some amount of energy into the system in order to gain more [7, 8]. Yet, the boundary between necessary passive actions and auxiliary active actions were vague until the introduction of the hybrid bias-flip solutions, such as energy injection [9], pre-biasing [10], and energy investment [11].

The aforementioned three hybrid solutions took double synchronized bias-flip actions for further increasing the harvested power under the same mechanical excitation [9-11]. Yet, it is not straight forward that double bias-flips solution must outperform the single one, i.e., the SSHI. For one thing, the timing and strength of each bias-flip action affect the harvested power a lot; more bias-flip actions implies more independent variables to be tuned towards optimization. For the other, if the bias-flip actions are not kept in good order or disordered by accident, the active energy injections might probably introduce an unstable factor to the PEH system. Given these uncertainties introduced by the hybrid bias-flip solutions, the author derived the optimal timing and strength of bias-flip actions towards maximum PEH capability in his recent work [12]. This paper continue on such a theoretical result, in order to get a proper and implementable circuit topology for PEH enhancement, which compromises all the factors of effectiveness, circuit complexity, as well as stability.

2. EVOLUTION OF PEH INTERFACE CIRCUITS

A vibrating piezoelectric structure generally outputs an ac voltage across its electrodes, which can be converted into dc with a rectifier for powering dc load and/or charging electrical storage. The bridge rectifier provides an interface for converting ac electricity into dc. It is universal and can be used for the conversion from different ac sources. Yet, the internal characteristics of different transducers in fact are different [3]. For example, piezoelectric transducer is usually characterized as an ideal current source in parallel with an inherent capacitance (neglecting the mechanical dynamics), as shown in Figure 1; while electromagnetic transducer is characterized as a voltage source in series with its self-inductance [13]. If the harvesting circuit is not designed as universal, but targeted at the unique features of a specific transduction mechanism, more harvested power might be obtained. This principle enables the continuous evolution of PEH interface circuits.

2.1 Standard Circuit

The initial comprehensive investigations of PEH circuit can be dated back to Ottman et al.'s work based on the universal bridge rectifier interface in 2002 [14, 15]. The same research group has also studied the damping effect induced by PEH system using such a universal electromechanical harvesting interface [16]. Ever after, the bridge rectifier is taken as the standard energy harvesting (SEH) interface circuit, and also provides a baseline for the later developments [17]; on the other hand, the objective of PEH optimization is extensively regarded as the same as increasing the electrical induced damping [18, 19]. The circuit topology and corresponding waveforms in SEH are shown in Figure 1(a) and (b), respectively. With SEH, each waveform cycle can be divided into two phases, i.e., open circuit and constant voltage, as distinguished by different background colors in Figure 1(b). It was demonstrated that the harvested power has a parabola relation versus the rectified voltage V_0. A maximum power point tracking (MPPT) should be implemented for maintaining the optimum operation [14, 15]. Moreover, as the product of current i_{eq} and voltage v_p is the power extracted from the vibrating structure, in order to maximize this power, we should tune v_p until it is in phase with i_{eq} (for unity power factor), and at the same time, enlarge the magnitude as much as possible. This idea leads to the inventions of a series of synchronized bias-flip interface circuits.

2.2 Passive Bias-Flip Circuits

The most notable and extensively investigated synchronized bias-flip circuits are the synchronized switch harvesting on inductor (SSHI) [4-6]. The circuit topology and corresponding operating waveforms of the parallel version of SSHI (P-SSHI) are shown in Figure 1(c) and (d); while those of the series version of SSHI (S-SSHI) are shown in Figure 1(e) and (f), respectively. It takes advantage of the capacitive nature of piezoelectric elements. At each synchronized instant, it opens a high-speed electrical shortcut for the charge stored in the piezoelectric capacitor, such that the piezoelectric voltage v_p can be modified to be in phase with the current i_{eq}. The charge movement might cease at a dc reference voltage V_b by using a non-resonant shortcut, e.g., the synchronized charge extraction (SCE) [20], or reach the overshooting extreme with respect to V_b by using a resonant (inductive) shortcut, e.g., P- and S-SSHI. Such instant voltage shifting is called voltage inversion [5] or bias-flip action [21].[1] Denoting the voltage before the bias-flip action as $U + V_b$, and that after the action as $U + \gamma V_b$, where γ is a scalar within $(-1, 1]$ called the inversion factor [22]. For each action, the energy input into the bias source is $C_p(1-\gamma)UV_b$. For the bias-flip actions of all the aforementioned solutions, we have

$$UV_b \geq 0\,, \tag{1}$$

which implies that the bias sources always absorb energy (greater sign), or just sustain in energy (equal sign). In this paper, these energy extractions (from the piezoelectric structure) are referred to as *passive bias-flip actions*. Since either of the SCE, P-SSHI, or S-SSHI has only one of such bias-flip action in each synchronized instant, we call them *passive bias-flip circuits*.

The synchronized bias-flip actions not only make v_p and i_{eq} in phase, but also enlarge the magnitude of v_p. Therefore, the passive bias-flip circuits can enhance the PEH capability by up to several hundred percent [4-6].

2.3 Hybrid Bias-Flip Circuits

Ever since the proposal of passive bias-flip circuits, a lot of research efforts have been put into their dynamic modeling [6, 22, 23], transformation [4], and implementation [24, 25]. On the other hand, evolution continued on. The direction for further PEH enhancement is clear, that is to further magnify the synchronized piezoelectric voltage v_p. But, how to achieve the goal? One answer is to artificially assign the waveform of v_p [8]. Yet, active voltage assignment requires a reverse flow of the harvested energy, which introduces a key problem that how we can make the ends meet? Nearly around a same period, Lallart and Guyomar [9], Dicken et al. [10], and Kwon and Rincon-Mora [11] come up with a series of similar solutions after the titles of energy injection [9], pre-biasing [10], and energy investment [11], respectively. Figure 1(g) and (h) show the circuit topology as well as operating waveforms of one of their derivatives, which is called single supply pre-biasing (SSPB) [10]. From Figure 1(g), the SSPB topology can be modified from the S-SSHI one by replacing the four diodes in the rectified bridge with four bi-directional switches. Such a replacement enable the reverse current flow from C_r to C_p, and so as the stored energy. From Figure 1(h), the profiles of SSPB and S-SSHI waveforms look the same; the difference lies on their synchronized instants as shown in the zoom-in views. The SSPB has experienced two bias-flip actions, rather than one in S-SSHI. The bias voltages in the both actions are V_b and $-V_b$, respectively; and zero is designated as the intermediate voltage connecting the two actions. More detailed operation can be referred to [10]. The double bias-flip actions in each synchronized instant enable the further increase of v_p magnitude under the same i_{eq}.

---

[1] In this paper, bias-flip rather than voltage inversion is used for highlighting the *bias voltage*, which is important for determining whether a flipping (or inversion) action is passive or active.

Looking into the details of the two bias-flips in each synchronized instant of SSPB, we can find that, the first one satisfy the condition described by (1); yet, for the second bias-flip, we have

$$UV_b < 0\ , \tag{2}$$

which implies that the bias sources absorb negative energy, in another word, inject energy into the piezoelectric structure. In this paper, these energy injections (to the piezoelectric structure) are referred to as *active bias-flip actions*. Some literature use a term "active PEH" for designating the solutions under the similar idea [8]. However, merely active actions do not provide harvestable energy; passive actions are compulsory for the purpose of energy harvesting. Given this ambiguity, we coin a new term *hybrid bias-flip circuits* for summarizing these harvesting solutions involving both active and passive bias-flip actions.

3. BEST VOLTAGE BIAS-FLIP STRATEGY

The underlying philosophy of hybrid bias-flip PEH circuits is to pay a reasonable amount of energy in order to gain more. Therefore, like most, if not all, of the financial investments, the rate of *return on investment* (ROI) should be the top concern. An analysis on the investment strategy is necessary towards a maximum ROI. Rigorous mathematics was done for deriving such a strategy based on a generalized synchronized multiple bias-flip (SMBF) topology, which is shown in Figure 2(a) [12]. The difference of SMBF from P-SSHI is that there are $2 \times M$ unidirectional bias-flip shortcuts in SMBF. Half of these switches and bias voltage sources, i.e., S_{+1} to S_{+M} and $V_{b,1}$ to $V_{b,M}$, enables the voltage shifting relay from positive to negative at a low energy cost, as shown in Figure 2(c); while the other half, i.e., S_{-1} to S_{-M} and reversed $V_{b,1}$ to $V_{b,M}$, enables the shifting relay from negative to positive.

Express the harvested power in terms of voltage variables, we have

$$E_h = 2\left[\textstyle\sum_{m=1}^{M}(1-\gamma)U_m V_{b,m} + (2-\Delta U)V_0\right]. \tag{3}$$

and then calculate the zero derivative point with respect to the intermediate voltages, such that we can obtain the optimal bias voltages set

$$\begin{cases} U_{m,opt} = \frac{1}{1+\gamma}\,, & m = 1,2,3,\dots,M \\ \Delta U_{opt} = 1 \end{cases} \tag{4}$$

which yields the maximum harvested power [12]. SMBF is general because when $\Delta U = 2$, it can be regarded as series SMBF (S-SMBF); when $0 < \Delta U < 2$, it can be regarded as parallel SMBF (P-SMBF). Figure 3(a) summarizes the maximum non-dimensional harvested power in SMBF as functions of inversion factor γ and flipping number of times M. The bias voltages in optimal S-SMBF is[2]

$$V_{b,m} = \frac{2\gamma+(1-\gamma)(M+2-2m)}{2(1+\gamma)}\,, \quad m = 1,2,3,\dots,M, \tag{5}$$

while those in P-SMBF is

$$V_{b,m} = \frac{1-\gamma}{1+\gamma}\frac{M-2m+1}{2}\,, \quad m = 1,2,3,\dots,M. \tag{6}$$

Figure 3(b) and (c) illustrates the corresponding optimal relay of voltage bias-flips towards such a maximum result in S-SMBF and P-SMBF, respectively. Since M is an integral number including 0 and 1, SEH, P-SSHI, and S-SSHI can be regarded as special cases of SMBF, as marked in Figure 3.

The theoretical best voltage bias-flip strategy does provide some useful insights and point out the possible way for the further improvement of PEH interface circuit. From Figure 3(a), it can be concluded

---

[2] The voltages mentioned here are non-dimensional voltage with respect to the piezoelectric open circuit voltage.

that, ideally, the harvesting capability can approach infinity from two directions: 1) enabling ideal voltage bias-flip, i.e., achieving inversion factor $\gamma \rightarrow -1$; and 2) sophisticatedly exerting more bias-flip actions, i.e., increase M, at each synchronized instant. Nevertheless, the former is constrained by the quality factor of the switching RLC path; while the latter seems difficult for realization, because large M requires many adaptive bias voltage sources and switch control, whose implementation is not that straight forward.

4. SYNCHRONIZED TRIPLE BIAS-FLIP (S3BF) INTERFACE CIRCUIT

The best voltage bias-flip strategy shows an ideal picture for the further improvement of PEH interface circuit. Yet, several considerations need to be taken before this strategy is able to facilitate future circuit improvements.

1) A good balance between the effectiveness of improvement and complexity of implementation should be made towards a significant and practical realization. On one hand, we would like to increase the bias-flip numbers M in order to enhance the harvested capability, as illustrated in Figure 3(a); on the other, M should not be too large in consideration of the implementation cost.
2) The bias voltage sources with adaptive voltage values are the most costly parts in practical implementation. In that sense, we should make the full use of each inserted bias voltage source.
3) Active intervention might be dangerous if the sources are not properly controlled or out of control by accident. It will be much better if the auxiliary bias source can be passive (charging by the piezoelectric system) and even self-adaptive. A passive auxiliary bias source enables the ultimate stability of the system, because the reversely injected energy is from nowhere, but the self-accumulation in historical cycles; total energy will not increase in spite of any misoperation.
4) The direction of current flow in each bias-flip action should be well controlled. The advancement of optimal SMBF relies on the amplification of v_p magnitude, which is achieved by continuous voltage relay in the synchronized instant. Without regulating the current direction, the voltage relay might not be heading a same direction and disorder the system.

Restricting that there is only one auxiliary voltage source provided, the highest PEH capability of the S-SMBF configuration is obtained when $M = 1$, i.e., S-SSHI; while that of the P-SMBF configuration is obtained when $M = 3$, i.e., synchronized triple bias-flip (S3BF) scheme, as marked in Figure 3(a) and (c). As we can observed by comparing Figure 3(b) and (c), or equation (5) and (6), because the bias voltages in the optimal condition of P-SMBF configuration is symmetry with respect to zero volt, in P-S3BF, the three bias voltage are V_b, 0, and $-V_b$, which can be obtained with one auxiliary voltage source V_b and one freely obtainable zero volt source.

4.1 Configuration and Operation

Taking the aforementioned four concerns into account, a new synchronized triple bias-flip (S3BF) circuit topology is developed as shown in Figure 4. The S3BF is composed of two paths, the series path for carrying out bias-flip actions and the parallel path for energy harvesting and storage. In each of the synchronized instant, v_p is successively exposed to three bias voltages, i.e., V_b, 0, and $-V_b$ in the positive to negative migration, or $-V_b$, 0, and V_b in the negative to positive one. In each bias-flip, the switching path has a series for restricting that the current flows in a desired direction. The auxiliary voltage source is realized with a capacitor in the series path. The capacitor can be self-charged or -discharged according to the harvesting condition. The capacitor here, which acts as a passive and self-adaptive voltage source, has eliminated many important issues, such as the origin of energy in the auxiliary bias source, adaptive control, and energy stability.

Half of the operational phases of S3BF, i.e., those in the positive to negative migration, are illustrated by the waveforms and current flow paths and shown in Figure 5. By properly control the switches in the synchronized instant, the S3BF repeats five phases in each a half cycle, i.e., open circuit, constant voltage, first bias-flip, second bias-flip, and third bias-flip.

4.2 Simulation results

The simulation results of S3BF with $i_{eq} = 100$ mA, $C_p = 34.69$ nF, and $\gamma = -0.42$ are obtained by PSIM and comparatively studied with SEH and SSHI in Figure 6. From the waveforms shown in Figure 6(a), the proposed circuit can properly function for providing triple bias-flip actions during the synchronized instant. The bias voltage source can be self-charged, as shown by the cyan line in Figure 6(a), rather than requiring external energy to run. The obtained v_p magnitude with S3BF is much larger than those in SSHI and SEH, which implies that the harvesting capability of S3BF outperforms the other two solutions. The harvested power in the three solutions are further investigated in Figure 6(b). In this specific case, it shows that the maximum harvestable power in S3BF, the peak, is about twice of that in SSHI and eight times of that in SEH.

5. CONCLUSIONS

The S3BF harvesting interface circuit, a new solution for piezoelectric energy harvesting (PEH) enhancement was proposed in this paper. Different from some previous circuit innovation, which were derived by modifying the existing circuit topologies, the S3BF was developed based the best bias-flip strategy, which generalizes the circuit evolution up to now and provides foresight for the future improvement. All important factors towards the implementation of hybrid bias-flip solutions, such as effectiveness of improvement, complexity of implementation, origin of energy in the bias voltage source, current regulation, as well as energy stability, are taking into consideration in the design of S3BF topology. Future effort should focus on the practical implementation of S3BF, in particular its driving circuit, and also the general electromechanical dynamic model of the SMBF based PEH systems.

ACKNOWLEDGMENTS

The work described in this paper was supported by the grant from National Natural Science Foundation of China (Project No. 61401277) and the Faculty Start-up Grant (Project No. F-0203-13-003) of ShanghaiTech University, Shanghai, China.

REFERENCES

[1] L. Tang, Y. Yang, and C. K. Soh, “Toward broadband vibration-based energy harvesting,” *J. Intell. Mater. Syst. Struct.*, vol. 21, no. 18, pp. 1867–1897, 2010.

[2] R. L. Harne and K. W. Wang, “A review of the recent research on vibration energy harvesting via bistable systems,” *Smart Materials and Structures*, vol. 22, no. 2, p. 023001, 2013.

[3] G. D. Szarka, B. H. Stark, and S. G. Burrow, “Review of power conditioning for kinetic energy harvesting systems,” *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 803 –815, Feb. 2012.

[4] D. Guyomar and M. Lallart, “Recent progress in piezoelectric conversion and energy harvesting using nonlinear electronic interfaces and issues in small scale implementation,” *Micromachines*, vol. 2, no. 2, pp. 274–294, 2011.

[5] D. Guyomar, A. Badel, E. Lefeuvre, and C. Richard, “Toward energy harvesting using active materials and conversion improvement by nonlinear processing,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 52, no. 4, pp. 584–595, 2005.

[6] Y. C. Shu, I. C. Lien, and W. J. Wu, “An improved analysis of the SSHI interface in piezoelectric energy harvesting,” *Smart Mater. Struct.*, vol. 16, no. 6, pp. 2253–2264, 2007.
[7] W. Q. Liu, Z. H. Feng, J. He, and R. B. Liu, “Maximum mechanical energy harvesting strategy for a piezoelement,” *Smart Mater. Struct.*, vol. 16, no. 6, pp. 2130–2136, 2007.
[8] Y. Liu, G. Tian, Y. Wang, J. Lin, Q. Zhang, and H. F. Hofmann, “Active piezoelectric energy harvesting: general principle and experimental demonstration,” *J. Intell. Mater. Syst. Struct.*, vol. 20, no. 5, pp. 575–585, 2009.
[9] M. Lallart and D. Guyomar, “Piezoelectric conversion and energy harvesting enhancement by initial energy injection,” *Appl. Phys. Lett.*, vol. 97, no. 1, p. 014104, 2010.
[10] J. Dicken, P. Mitcheson, I. Stoianov, and E. Yeatman, “Power-extraction circuits for piezoelectric energy harvesters in miniature and low-power applications,” *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4514–4529, 2012.
[11] D. Kwon and G. A. Rincon-Mora, “Energy-investment schemes for increasing output power in piezoelectric harvesters,” in *IEEE 55th International Midwest Symposium on Circuits and Systems*, aug. 2012, pp. 1084–1087.
[12] J. R. Liang and H. S.-H. Chung, “Best voltage bias-flipping strategy towards maximum piezoelectric power generation,” *J. Phys. Conf. Ser.*, vol. 476, no. 1, p. 012025, 2013.
[13] A. Khaligh, P. Zeng, and C. Zheng, “Kinetic energy harvesting using piezoelectric and electromagnetic technologies – state of the art,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 850–860, March 2010.
[14] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, “Adaptive piezoelectric energy harvesting circuit for wireless remote power supply,” *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 669–676, 2002.
[15] G. K. Ottman, H. F. Hofmann, and G. A. Lesieutre, “Optimized piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode,” *IEEE Trans. Power Electron.*, vol. 18, no. 2, pp. 696–703, March 2003.
[16] G. A. Lesieutre, G. K. Ottman, and H. F. Hofmann, “Damping as a result of piezoelectric energy harvesting,” *J. Sound Vib.*, vol. 269, no. 3-5, pp. 991–1001, 2004.
[17] J. R. Liang and W. H. Liao, “Piezoelectric energy harvesting and dissipation on structural damping,” *J. Intell. Mater. Syst. Struct.*, vol. 20, no. 5, pp. 515–527, 2009.
[18] L. M. Miller, P. D. Mitcheson, E. Halvorsen, and P. K. Wright, “Coulomb-damped resonant generators using piezoelectric transduction,” *Appl. Phys. Lett.*, vol. 100, no. 23, p. 233901, 2012.
[19] Y. Wang and D. J. Inman, “A survey of control strategies for simultaneous vibration suppression and energy harvesting via piezoceramics,” *J. Intell. Mater. Syst. Struct.*, vol. 23, no. 18, pp. 2021–2037, 2012.
[20] L. Tang and Y. Yang, “Analysis of synchronized charge extraction for piezoelectric energy harvesting,” *Smart Mater. Struct.*, vol. 20, no. 8, p. 085022, 2011.
[21] Y. Ramadass and A. Chandrakasan, “An efficient piezoelectric energy harvesting interface circuit using a bias-flip rectifier and shared inductor,” *IEEE J. Solid-State Circuits*, vol. 45, no. 1, pp. 189–204, Jan. 2010.
[22] J. R. Liang and W. H. Liao, “Impedance modeling and analysis for piezoelectric energy harvesting systems,” *IEEE/ASME Trans. Mechatron.*, vol. 17, no. 6, pp. 1145 –1157, 2012.
[23] I. C. Lien, Y. C. Shu, W. J. Wu, S. M. Shiu, and H. C. Lin, “Revisit of series-SSHI with comparisons to other interfacing circuits in piezoelectric energy harvesting,” *Smart Mater. Struct.*, vol. 19, no. 12, p. 125009, 2010.
[24] M. Lallart and D. Guyomar, “An optimized self-powered switching circuit for non-linear energy harvesting with low voltage output,” *Smart Mater. Struct.*, vol. 17, no. 3, p. 035030, 2008.
[25] J. R. Liang and W. H. Liao, “Improved design and analysis of self-powered synchronized switch interface circuit for piezoelectric energy harvesting systems,” *IEEE Trans. Ind. Electron.*, vol. 59, no. 4, pp. 1950–1960, 2012.

[26] ——, “Energy flow in piezoelectric energy harvesting systems,” *Smart Mater. Struct.*, vol. 20, no. 1, p. 015005, 2011.

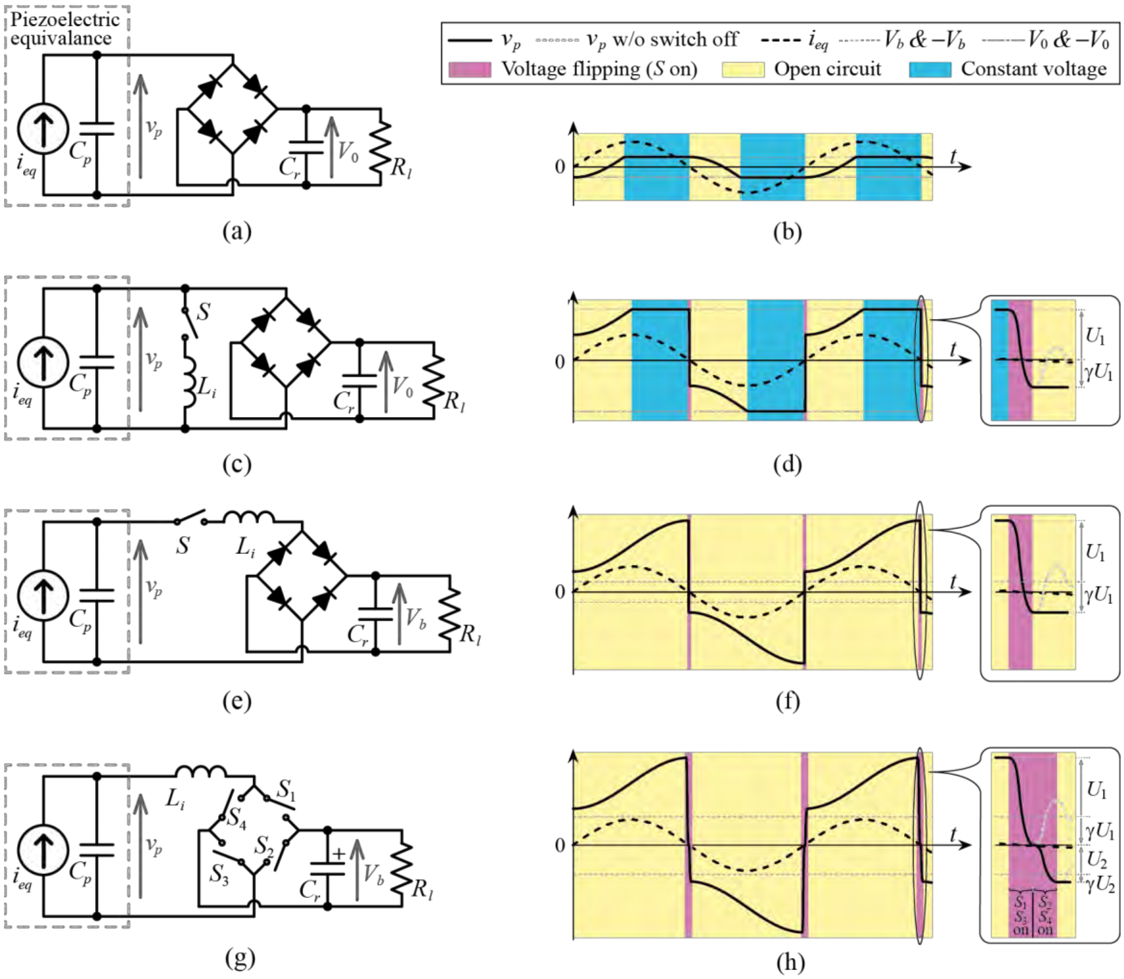
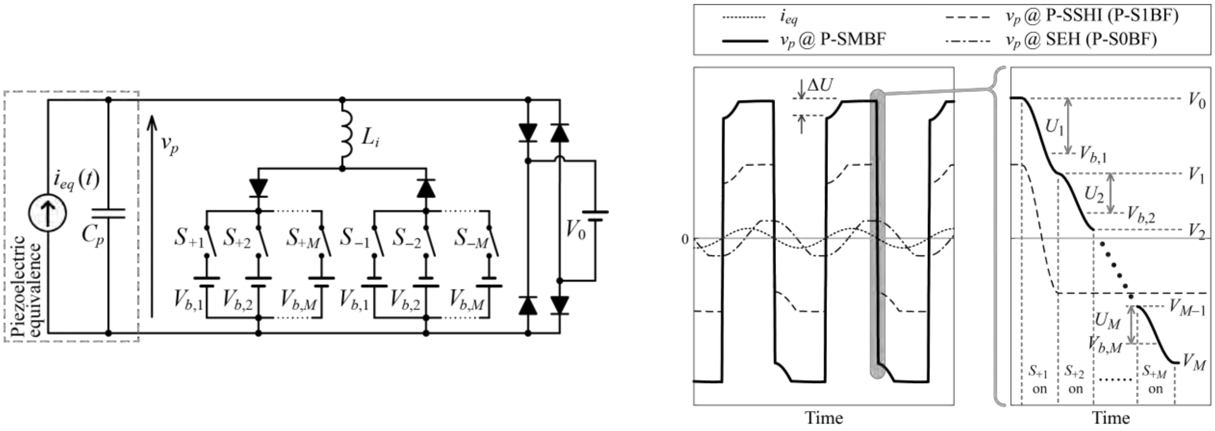
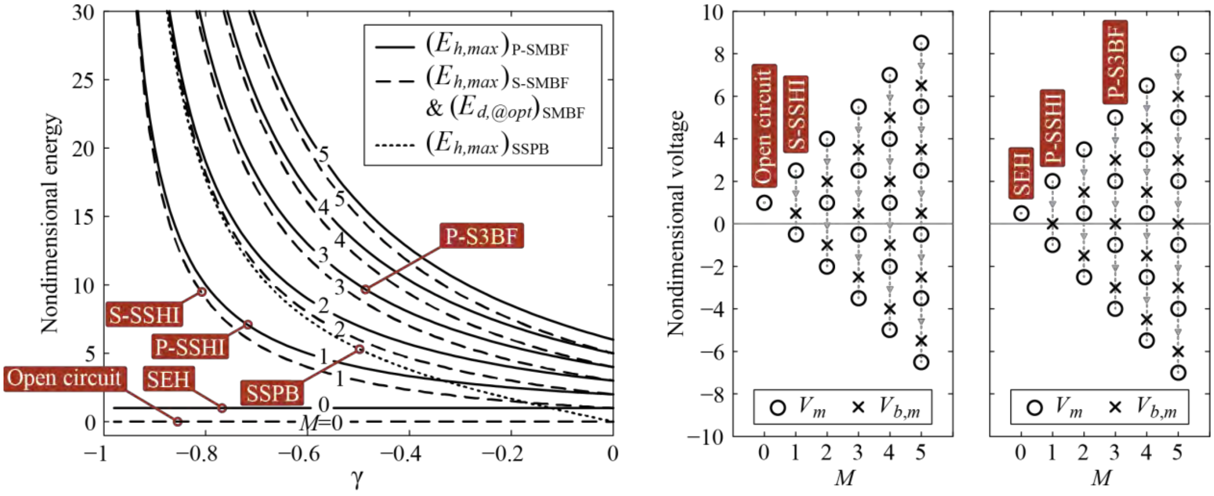


Figure 1. The evolution of PEH interface circuits. Topologies: (a) SEH, (c) P-SSHI, (e) S-SSHI, (g) SSPB. Operating waveforms: (b) SEH, (d) P-SSHI, (f) S-SSHI, (h) SSPB.



(a) (b) (c)

Figure 2. Generalized SMBF. (a) Circuit Topology [12]. (b) Operating waveforms [12]. (c) Zoom-in view of the synchronized instant.



(a) (b) (c)

Figure 3. Optimal SMBF including open circuit, SEH, S-SSHI, P-SSHI, SSPB, and P-S3BF as some of their special cases. (a) Maximum non-dimensional harvested energy. (b) and (c) Optimal intermediate and bias voltages in the positive to negative voltage bias-flip relay in S-SMBF (b) and P-SMBF (c), respectively.

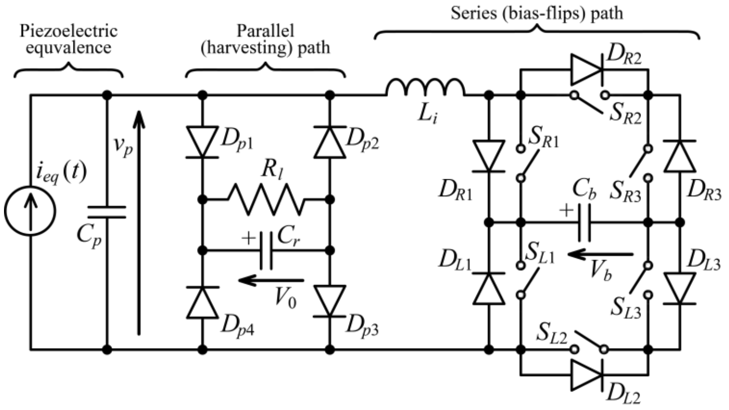
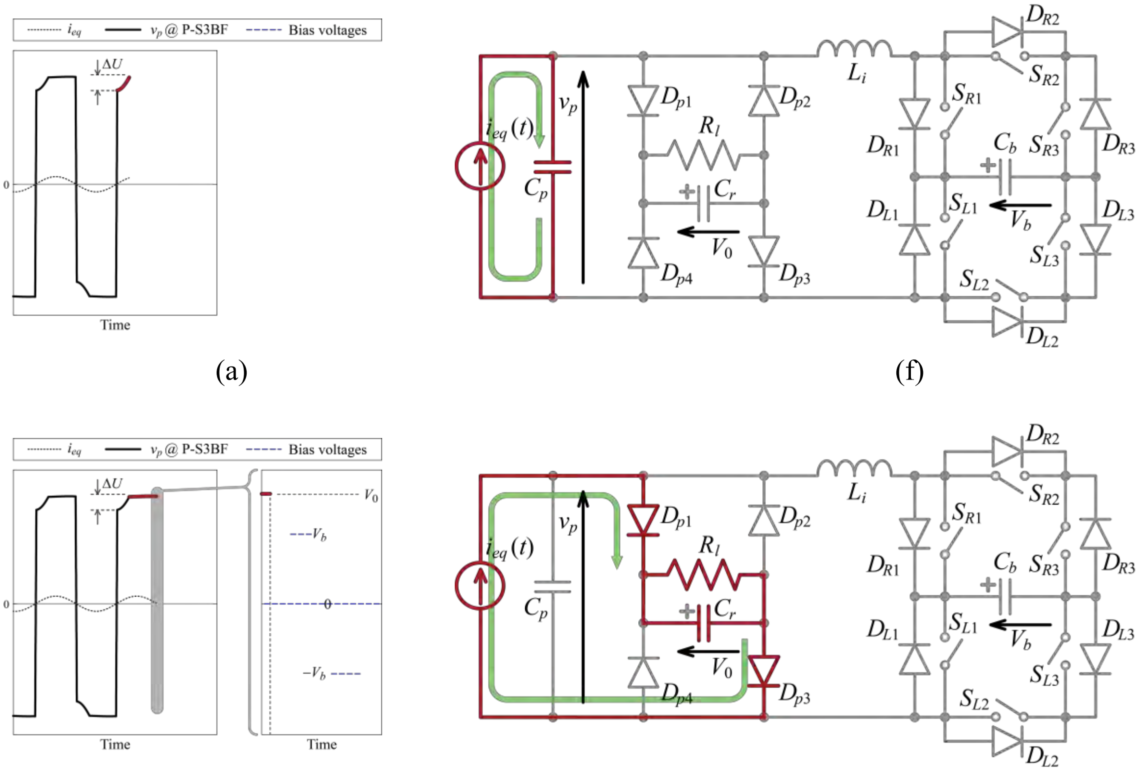
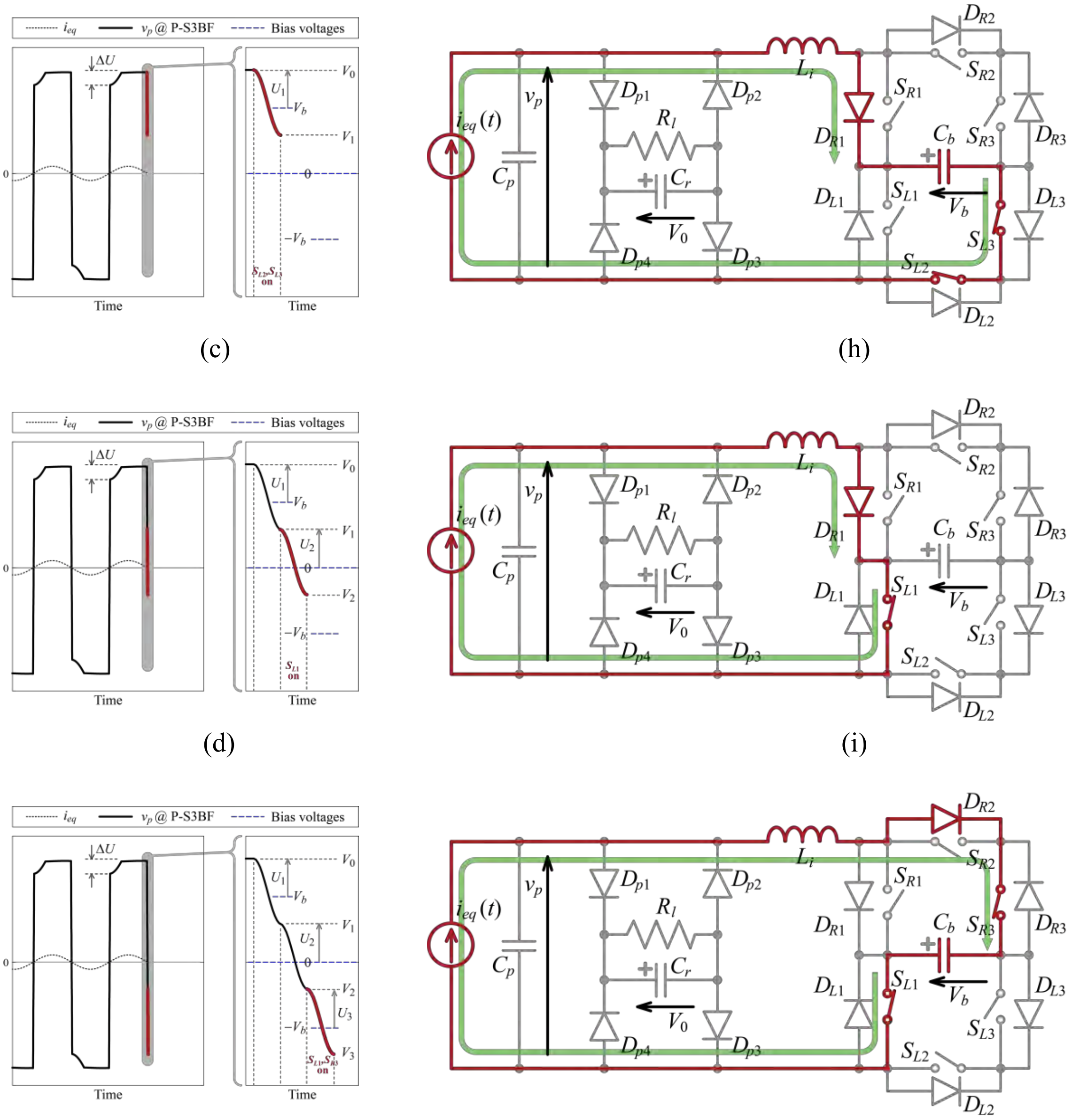


Figure 4. S3BF circuit topology.



(a) (f)

(b) (g)

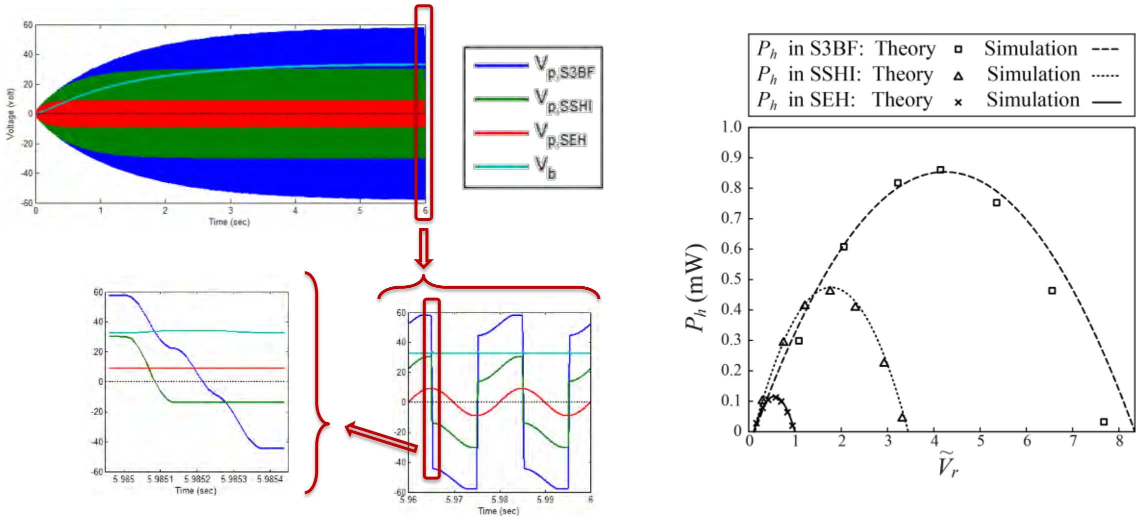


(c) (h)

(d) (i)

(e) (j)

Figure 5. Half of the working phases in S3BF. (a)-(e) Waveforms. (f)-(j) Current flow paths. (a) and (f) Open circuit. (b) and (g) Constant voltage. (c) and (h) First bias-flip. (d) and (i) Second bias-flip. (e) and (j) Third bias-flip.



(a)

(b)

Figure 6. Simulation results of S3BF.
(a) Waveforms and their zoom-in views (in color). (b) Harvested power.