Phase-Variable Control of Parallel Synchronized Triple Bias-Flips Interface Circuit towards Broadband Piezoelectric Energy Harvesting

Bao Zhao, Junrui Liang, and Kang Zhao
School of Information Science and Technology
ShanghaiTech University, Shanghai 201210, China
Email: {zhaobao, liangjr, zhaokang}@shanghaitech.edu.cn

Abstract—This paper introduces a new phase-variable switch control for the parallel synchronized triple bias-flip (P-S3BF) interface circuit, towards the broadband and high-capability piezoelectric energy harvesting (PEH) systems. By using the phase-variable P-S3BF (PV-P-S3BF), both the electrically induced damping and electrically induced mass/stiffness can be tuned to a certain extent in operation, such that to simultaneously make the dual tasks of broadband and high-capability in PEH. The joint dynamics and harvested power of the PEH systems using the PV-P-S3BF circuits are thoroughly discussed based on the harmonic analysis and impedance modeling. The available range of PV-P-S3BF is rationally shown in the complex impedance plane. The experimental results obtained with a PCB-level prototyped circuit show agreement with the analytical results. The new PV-P-S3BF circuit opens a promising future towards the electrically in-situ tunable broadband and high-capability PEH systems.

I. INTRODUCTION

The piezoelectric energy harvesting (PEH) technology provides solutions for converting the ambient kinetic energy into useful electricity, such that to enable some highly distributed Internet of Things (IoT) devices, which operate in vibrational environments, to become energy-self-sufficient. The two most significant research targets in this area are: 1) to enhance the energy harvesting capability in resonance, and 2) to broaden the bandwidth of the harvester; in order words, to enhance the off-resonance harvesting capability. The circuit solutions have shown significant contributions for making the first goal [1]. On the other hand, the second goal has been extensively investigated by adopting different mechanical designs [2]: electrical engineers contributed little towards the broadband task for long. The reason is due to the weakly or moderately coupling feature of most piezoelectric structures. The reverse piezoelectric effect was not strong enough to intervene the electrical coupling feature of most piezoelectric structures. The reverse piezoelectric effect was not strong enough to intervene the mechanical vibration without advanced circuit solutions.

New interface circuits keep being proposed during the last decade since the first synchronized switch harvesting on inductor (SSHI) [3]. Shu et al. [4] have pointed out that, by using the synchronized switch circuit solutions, a weakly coupled PEH system might become a moderately or strongly coupled system. The dynamic tuning now is possible to be realized to some extent by using the circuit solutions with higher PEH capability. Recently, some solutions have investigated how to enhance the off-resonance performance by introducing a switching delay in SSHI [5] or the synchronous charge extraction (SCE) circuits [6]. Such technology is referred to as PV-SSHI and PV-SCE in short in the following parts of this paper.

This paper explores the broadband performance of the PEH systems based on an up-to-date and more capable PEH interface circuit, the parallel synchronized triple bias-flip (P-S3BF) [7]. By introducing a second tunable variable, i.e., the switching delay, to P-S3BF, the energy harvesting bandwidth can be further broadened beyond other existing circuit solutions.

II. P-S3BF INTERFACE CIRCUIT [7]

The P-S3BF circuit is a special implementation of the synchronized multiple bias-flip (SMBF) conception [8]. The basic idea of SMBF is to maximize the power extraction from the piezoelectric source with minimum dissipative effort. Such compromise can be realized by sophisticatedly combining
multiple small voltage-changing steps (for less dissipated energy) through switching transients, such that to produce a large voltage jump (for more extracted energy) at each synchronized instant. The circuit topology and the operating waveforms of P-S3BF, i.e., the parallel and \( M = 3 \) version of SMBF, is shown in Fig. 1.

The piezoelectric equivalent is composed of a current source \( i_{eq} \), which is proportional to vibration velocity, \( C_p \) the piezoelectric clamped capacitance, and \( R_p \) the leakage resistance representing the effect of dielectric loss, as shown in Fig. 1(a). When \( i_{eq} \) crosses zero from positive to negative, the MOSFET switches take actions by conducting the \((M_{R1} \text{ and } M_{L2}), M_{L1}, \text{ and } (M_{R3} \text{ and } M_{L1})\) in succession (each for half of an \( L_i C_p \) cycle), such that to change \( v_p \) the voltage across the piezoelectric element in a triple-step downstairs shape, as shown in Fig. 1(c). On the other hand, when \( i_{eq} \) crosses zero from negative to positive, the reciprocal switches are turned on in succession for making a triple-step upstairs change of \( v_p \), as shown in Fig. 1(d). Through those switching actions, \( v_p \) is made in phase with \( i_{eq} \) and its magnitude is boosted to a much higher level, as shown in Fig. 1(b); therefore, the extracted energy in each cycle is largely increased. On the other hand, small voltage steps help eliminate the switching loss. In general, P-S3BF outperforms SSSI regarding net harvested power under the same vibration excitation. Or simply puts, P-S3BF has higher energy harvesting capability [7].

Enhancing the harvesting capability is the major, if not the only, goal of interface circuit development since the early studies on the PEH interface circuit [9]. Such target was realized by increasing the electrically induced damping in the weakly coupled PEH systems. Or, expressing in an electrical way, to increase the equivalent load resistance observed from the equivalent current source \( i_{eq} \). It was observed through the impedance modeling that, SSSI outperforms the standard energy harvesting (SEH) bridge rectifier circuit because it can enlarge the equivalent real part, i.e., the resistive component, of the equivalent impedance of the electrical part in a PEH system. Likewise, P-S3BF outperforms SSSI because it further enlarges the equivalent real part of such impedance [7].

III. PV-P-S3BF TOWARD BROADBAND PEH

No matter in SEH, parallel SSSI (P-SSI), series SSSI (S-SSI), or P-S3BF, there is only one tunable variable, i.e., the rectified voltage across the filter capacitor, like \( V_r \) in Fig. 1(a). Fig. 2(a) shows the general equivalent impedance network of the single-variable tunable circuits [10]. In the impedance network, the series connected \( R, L, \) and \( C \) form the resonant path, whose resonance frequency corresponds to the short-circuit piezoelectric structure; \( X_c, R_h, \) and \( R_d \) are the electrically induced reactance, regenerative resistance, and dissipative resistance, respectively. The electrical part in Fig. 2 is consisted of these three components and \( C_p \), which also influence the equivalent impedance \( Z_e \) [11]. The values of \( X_c, R_h, \) and \( R_d \) depend on the specific type of interface circuit in use. They can be identified and quantified with the harmonic analysis and impedance modeling [11]. Besides, a leakage resistance \( R_p \), which is connected in parallel with \( C_p \) and the circuit, represents the dielectric loss effect in practical piezoelectric materials [10].

In the single-variable tunable PEH circuits, the values of \( X_c, R_h, \) and \( R_d \) are functions of the nondimensionalized rectified voltage \( V_r \). Changing \( V_r \) makes their sum \( Z_e \) move along the corresponding one-dimensional trajectory in the two-dimensional complex impedance plane [11]. The trajectories of some extensively discussed circuits are shown in Fig. 3. Since most of the trajectories are close to the real axis, all the existing single-variable tunable solutions can hardly produce comparative electrically induced mass (corresponds to inductive \( X_c \)) or stiffness (corresponds to capacitive \( X_c \)) to counteract the imaginary source impedance at off-resonance conditions. In other words, their resonance-tuning capabilities are weak.

The adjustment of the equivalent imaginary part can be made by introducing the second tunable variable, the switching phase. It is realized by making lead or lag to the switch instants without changing the circuit topology. By tuning two circuit variables, the available range of the equivalent impedance becomes a two-dimensional area in the complex impedance plane. Fig.3 shows the available regions of \( Z_e \) in phase-variable SSSI (PV-SSI) and phase-variable P-S3BF (PV-
P-S3BF). Compared to other existing solutions, PV-P-S3BF not only allows the largest extent of equivalent resistance so far (corresponds to damping in the mechanical domain) towards higher energy harvesting capability, but also enlarges the available range of equivalent reactance (corresponds to mass/stiffness in the mechanical domain) towards better resonance-tuning capability. Such concept is illustrated in the equivalent impedance networks in Fig. 2(b).

Fig. 4 shows the detailed waveforms of PV-P-S3BF in three cases with switch phase lead, in-phase condition, and switch phase lag. The phase lag between the switching instant and the zero-crossing instant of \( i_{eq} \) is denoted as a new variable \( \varphi \). Therefore, Fig. 4(a)-(c) correspond to the negative, zero, and positive \( \varphi \) cases, respectively. The corresponding positions of \( Z_e \) in the three cases are shown in Fig. 4(d)-(f), respectively. Their values can be quantified with the harmonic analysis and impedance modeling [11].

As we can observe from Fig. 4(a), negative \( \varphi \) makes \( v_p \) lead \( i_{eq} \), which produces positive \( X_e \) in Fig. 4(d). It introduces an additional mass to the mechanical vibrator and decreases its resonant frequency. On the contrary, positive \( \varphi \) makes \( v_p \) lag \( i_{eq} \), which produces negative \( X_e \), i.e., an additional stiffness for increasing the resonant frequency. Therefore, by introducing the switching phase \( \varphi \) as a new tunable variable, the tunable range of \( Z_e \) has been extended vertically towards a larger imaginary part for tuning the resonance of the PEH system.

IV. IMPEDANCE MODELING

This section quantifies the value of \( Z_e \), as well as its detailed constitutive components, i.e., \( X_e \), \( R_h \), and \( R_d \), in PV-P-S3BF by harmonic analysis and impedance modeling. The harmonic analysis begins from assuming sinusoidal \( i_h \), the current flowing through \( Z_e \), i.e.,

\[
i_h(t) = I_h \sin(\omega t), \tag{1}
\]

where \( \omega \) is the vibration frequency, \( I_h \) is the magnitude of \( i_h \). We define the phase differences from the switching point and rectifier-conducting point to the zero-crossing point of \( i_h \) as \( \varphi \) and \( \theta \) respectively, as illustrated in Fig. 4(a)-(c). When \( \varphi \in [-\pi/2, 0] \) and \( \theta \in [-\varphi, \pi + \varphi] \), the switch lead condition is shown in Fig. 4(a). By assuming the bias-flip actions take much less time than a vibration cycle, the piezoelectric voltage \( v_p \) can be formulated with the piecewise equations as follows

\[
v_p(t) = V_{oc} \times \begin{cases} 
-V_3 + \cos \varphi - \cos(\omega t), & \varphi \leq \omega t < \theta; 

-V_3 + \cos \varphi - \cos \theta, & \theta \leq \omega t < \pi + \varphi; 

\tilde{V}_3 - \cos \varphi - \cos(\omega t), & \pi + \varphi \leq \omega t < \pi + \theta; 

\tilde{V}_3 - \cos \varphi + \cos \theta, & \pi + \theta \leq \omega t < 2\pi + \varphi; 
\end{cases} \tag{2}
\]

where \( \tilde{V}_3 = V_3/V_{oc} \) is the nondimensionalized \( V_3 \), end voltage of the downstairs actions, whose meaning is illustrated in Fig. 1(c); \( V_{oc} = I_h/(\omega C_p) \) is the nominal open-circuit voltage. The value of \( \tilde{V}_3 \) can be obtained by solving the following linear equations

\[
\begin{bmatrix}
1 & \gamma -1 & \gamma \\
\gamma -1 & -1 & \gamma \\
1 & -1 & -1
\end{bmatrix} \begin{bmatrix}
\tilde{V}_0 \\
\tilde{V}_1 \\
\tilde{V}_2 \\
\tilde{V}_3
\end{bmatrix} = \begin{bmatrix}
\cos \varphi - \cos \theta \\
0 \\
0 \\
0
\end{bmatrix}, \tag{3}
\]

where \( \gamma \) is the flipping factor of each voltage bias flip [8]. For the switch lag condition, where \( \varphi \in (0, \pi/2] \) and \( \theta \in [\cos^{-1}(2\cos \varphi - 1), \pi] \),

\[
v_p(t) = V_{oc} \times \begin{cases} 
-V_3 + \cos \varphi - \cos(\omega t), & \varphi \leq \omega t < \theta; 

-V_3 + \cos \varphi - \cos \theta, & \theta \leq \omega t < \pi; 

\tilde{V}_3 - \cos \varphi - \cos(\omega t - \cos \theta - 1), & \pi \leq \omega t < \pi + \varphi; 

\tilde{V}_3 - \cos \varphi - \cos(\omega t) + \cos \theta + 1, & 2\pi \leq \omega t < 2\pi + \varphi; 
\end{cases} \tag{4}
\]

where \( \tilde{V}_3 \) can be obtained by solving the equations as follows

\[
\begin{bmatrix}
1 & \gamma -1 & \gamma \\
\gamma -1 & -1 & \gamma \\
1 & -1 & -1
\end{bmatrix} \begin{bmatrix}
\tilde{V}_0 \\
\tilde{V}_1 \\
\tilde{V}_2 \\
\tilde{V}_3
\end{bmatrix} = \begin{bmatrix}
2 \cos \varphi - \cos \theta - 1 \\
0 \\
0 \\
0
\end{bmatrix}. \tag{5}
\]

With the piecewise expression of \( v_p \), we can further obtain its fundamental harmonic \( v_{p,f} \) by doing the Fourier analysis [11]. The pictures of \( v_{p,f} \) under the leading, in-phase, and laggng conditions are also shown in Fig. 4(a)-(c). The equivalent impedance can be formulated from the frequency expressions of \( V_{p,f} \) and \( I_h \), i.e.,

\[
Z_e(j\omega) = \frac{V_{p,f}(j\omega)}{I_h(j\omega)} = R_h + R_d + jX_e. \tag{6}
\]

\( Z_e \) is a function of \( \omega \), \( \theta \) (related to the nondimensionalized rectified voltage \( \tilde{V}_r \)), and \( \varphi \). Therefore, given any deviation
An electromagnetic sensor mounted at the free end of the parameters are shown in Table I, is excited by a shaker. Switches are controlled by a Texas Instrument MSP430 microprocessor. PV-P-S3BF experiments. The switching sequence is delivered by carrying out the phase-variable switch control on an established P-S3BF prototyped circuit [7]. The improvement in energy harvesting bandwidth by using PV-P-S3BF is checked and validated by experiments on practical PEH systems. The theoretical prediction on harvested power needs to be provided for better understanding and quantification of the attainable range of equivalent impedance of PV-P-S3BF is 160.7% broader than that of SEH, as shown in Fig. 6(b). Experimental results agree with the theory in general. The bandwidth broadening effect of PV-P-S3BF is successfully validated.

V. EXPERIMENTAL VALIDATION

The experimental PV-P-S3BF interface circuit is implemented by carrying out the phase-variable switch control on an established P-S3BF prototyped circuit [7]. The improvement in energy harvesting bandwidth by using PV-P-S3BF is checked in the experiment. Fig. 5 shows the prototyped circuit for the PV-P-S3BF experiments. The switching sequence is delivered by six MOSFET switches, as shown in Fig. 1. The electronic switches are controlled by a Texas Instrument MSP430 microcontroller, as shown in Fig. 5. A piezoelectric cantilever, whose parameters are shown in Table I, is excited by a shaker. An electromagnetic sensor mounted at the free end of the cantilever senses the vibration velocity for the synchronization purpose.

Fig. 6 shows the maximum harvested power \( P_h \) under different vibration frequencies and switching phase \( \phi \) in the SEH and PV-P-S3BF cases. The \( \phi = 0 \) case is just P-S3BF. The maximum \( P_h \) in PV-P-S3BF is the envelope of the power curves under different \( \phi \). It can be observed from Fig. 6 that the half-maximum-power bandwidth \( \Delta \omega_{HM} \) (also referred to as the \( -3 \) dB bandwidth in [5]) of PV-P-S3BF is 16.3% broader than that of P-S3BF, and is 96.2% broader than that of SEH. The bandwidth broadening effect is more pronounced if we take the half of the maximum power in SEH as the baseline reference. The SEH referenced bandwidth \( \Delta \omega_{SR} \) of PV-P-S3BF is 160.7% broader than that of SEH, as shown in Fig. 6(b). Experimental results agree with the theory in general. The bandwidth broadening effect of PV-P-S3BF is successfully validated.

VI. CONCLUSION

A new circuit solution, the phase-variable parallel synchronized triple bias flip (PV-P-S3BF) interface circuit was introduced in this paper for broadening the energy harvesting bandwidth of the piezoelectric energy harvesting (PEH) systems. The working principle and impedance modeling are provided for better understanding and quantification of the electromechanical joint dynamics and harvested power by using PV-P-S3BF. Experiments are carried out for validating the theoretical analysis. The proposed solution and analysis provide a new insight towards the designs of broadband PEH systems.

Fig. 5. Prototyped circuit of the PV-P-S3BF experiments [7].

Fig. 6. Harvested power \( P_h \). (a) SEH. (b) PV-P-S3BF.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<td>( R )</td>
<td>57.41 k( \Omega )</td>
<td>( L )</td>
<td>2.65 k( \Omega )</td>
</tr>
<tr>
<td>( L )</td>
<td>57.83 n( \mu )F</td>
<td>( C_r )</td>
<td>0.47 n( \mu )F</td>
</tr>
<tr>
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<td>57.41 k( \Omega )</td>
<td>( Z_m )</td>
<td>47 n( \Omega )</td>
</tr>
<tr>
<td>( Z_m )</td>
<td>4.7 ( \Omega )</td>
<td>( R )</td>
<td>679.96 k( \Omega )</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>-0.5</td>
<td>( \phi )</td>
<td>30°</td>
</tr>
</tbody>
</table>

PV-P-S3BF (\( \phi = 0° \)) experiment SEH experiment PV-P-S3BF (\( \phi = 30° \)) theory PV-P-S3BF (f = 30°) experiment PV-P-S3BF (f = 0°, i.e., P-S3BF) theory PV-P-S3BF (f = 0°, i.e., P-S3BF) experiment

TABLE I

SPECIFICATIONS OF THE EXPERIMENTAL PEH SYSTEM.
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