A three-port power electronic interface to harvest the maximum power in electromagnetic energy harvesting systems

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Abstract—In conventional electromagnetic energy harvesting systems, a two-port pulse-width-modulated ac/dc converter is utilized to process the harvested power. However, it is difficult to achieve voltage regulation and maximum-power-point tracking simultaneously. To resolve this issue, this paper proposes a three-port power-electronic-interface for this specific application. A battery is introduced to buffer the redundant energy in harvest mode. A bidirectional dc/dc converter is utilized to regulate the load side voltage. Thus, the regulations of power and voltage are fully decoupled, which makes it easier to trace the maximum-power-point. Moreover, when the harvester is in idle mode, the battery provides power to the load via the bidirectional dc/dc converter. A 10 mW rated converter prototype, which processes the power flow among a 0.6 V, 100 Hz ac source, a 1.2 V battery, and a 3.3 V constant voltage load is developed and tested. The proposed concept is validated by experimental results.

Index Terms—bi-directional buck/boost converter, bridgeless rectifier, energy harvesting, maximum-power-point tracking (MPPT), three-port.

I. INTRODUCTION

Energy harvesting technology is crucial to achieve energy self-sufficient internet-of-things (IoT) systems [1], [2]. Among different energy harvesting mechanisms, electromagnetic (EM) harvester outperforms in high power density and has attracted wide attention. The output of EM harvester is typically a low voltage [3], low power ac voltage, which needs to be boosted by an ac/dc power electronic interface (PEI) to supply stable power to the IoT loads.

The electric power generated from the EM harvester is often vulnerable to environmental variations [4]. While the IoT loads might consume stable power in active mode. This leads to the power mismatch between the harvester and load. Moreover, the load usually requires a well-regulated voltage. However, if the PEI operates in voltage regulation mode, the maximum-power-point (MPP) tracking cannot be realized simultaneously. Therefore, the power match, MPP tracking, and voltage regulation should be all satisfied when designing the PEI.

Traditional two-stage ac/dc PEI with diode bridge is unsuitable here due to the high diode forward voltage. In [3], [5]–[7], several direct ac/dc PEIs without diode bridge are reported. However, only voltage regulation is implemented. The power mismatch between generator and load is not addressed. In [8]–[10] two three-port PEIs are proposed to address the power mismatch problem. However, the converters are mainly investigated for high power applications. In [4], a three-port zero-voltage-switching (ZVS) PEI is proposed to enhance the efficiency of energy harvesting system. However, this PEI can only interface with two dc inputs. It cannot be deployed to EM harvesting systems. In [11], a three-port ac/dc PEI is investigated to harvest wind energy at low cutoff wind speeds. However, MPP tracking is not addressed. In [5], an MPP tracking method is proposed in low-power energy harvesting systems. However, the MPP is realized with sacrificed voltage regulation performance.

To improve, this paper proposes a three-port PEI to track the MPP of the low voltage EM harvester. The power match between load and generator, MPP tracking, and load side voltage regulation can be synergistically realized. The battery and the linkage bidirectional dc/dc converter serve as the buffer to achieve all those three targets. In addition, both the system reliability and the renewable energy utilization are enhanced. Moreover, zero-current-switching and ZVS techniques are enforced to enhance the efficiency of the PEI.

This paper is organized as follows: Section II introduces the operation principles of proposed topology. Detailed design guidelines are provided in Section III. In Section IV, the hardware implementation is presented. Section V demonstrates experimental results. Finally, the paper concludes in Section VI.

II. OPERATION PRINCIPLES

Fig. 1 shows the schematic of the proposed three-port PEI, where a bridgeless rectifier and a bi-directional buck/boost converter are used to connect the ac source, load and battery. $Z_{in}$ represents the equivalent source impedance of micro-
A. Bi-directional buck/boost converter

As commented before, the output voltage is regulated by the bi-directional buck/boost converter. As shown in Fig. 2, the bi-directional buck/boost converter links the load and the battery. \( V_b \) represents a rechargeable battery which can be either charged or discharged. Usually, the terminal voltage of the rechargeable battery is lower than output voltage. Hence, the battery is placed on the low voltage side. \( S_3 \) and \( S_4 \) conduct alternatively. Therefore, bi-directional buck/boost converter can only operate in continuous conduction mode (CCM) due to the lack of ability to block the reverse current. The relationship between \( V_o \) and \( V_b \) always satisfies:

\[
V_o = \frac{V_b}{d_3}
\]

where \( d_3 \) is the duty cycle of \( S_3 \). Therefore, \( V_o \) could be tightly regulated via closed-loop control.

As shown in Fig. 2, the bi-directional buck/boost converter can operate in buck, boost and boundary states depending on the averaging current of \( L_2 \). At steady state, the converter operates in buck state when the average current of \( L_2 \) is positive. Electrical power is transferred from high voltage side to low voltage side in an average period. On the contrary, the converter operates in boost mode when the average current of \( L_2 \) is negative. There isn’t energy exchange over an average period when the average current of \( L_2 \) is zero in boundary state.

ZVS of \( S_4 \) can be realized due to the negative current of \( L_2 \). When \( S_3 \) is turned off while \( S_4 \) hasn’t been turned on, \( L_2 \) resonates with the equivalent output capacitor of \( S_3 \) and \( S_4 \). The bode diode of \( S_4 \) conducts when \( V_{ds} \) of \( S_4 \) resonates to zero. Thus, ZVS of \( S_1 \) can be realized. The mechanism of \( S_3 \)’s ZVS functions in a similar way.

B. Bridgeless rectifier

The basic purpose of this bridgeless rectifier is to rectify the ac voltage from the harvester to a boosted dc voltage. Practically, the output of the harvester is an irregular ac voltage with its frequency and the magnitude varying. In this paper, an ideal sinusoidal ac voltage is used to emulate the output of the harvester to analyze the circuit operation. It can be represented as

\[
v_{\text{in}}(t) = V_1 \sin(2\pi t/T_{\text{in}})
\]

where \( V_1 \) is the magnitude of the input voltage and \( T_{\text{in}} \) is the period. The input capacitor can be assumed as a low pass filter. Thus, the voltage of \( C_1 \) can be represented as

\[
v_{c_1}(t) = V_{c_1} \sin(2\pi t/T_{\text{in}})
\]

\( V_{c_1} \) is the magnitude of the capacitor voltage which is lower than \( V_1 \) due to the influence of source impedance. \( V_o \) is the tightly regulated output voltage to enable the normal operation of IoT loads. The electric load is emulated by an equivalent resistor \( R_o \).

A single-stage boost-type bridgeless rectifier for low-voltage systems is adopted to achieve the high step-up ac/dc converter. In the positive half cycle, \( S_2 \) is always on and \( S_1 \) operates as the main switch. On the contrary, in the negative half cycle, \( S_1 \) is always on and \( S_2 \) operates as the main switch. Therefore, a voltage polarity detector is required to detect the voltage polarity. The input current waveform is shown in Fig. 3. Two boost topologies function in the positive and negative half input cycle. It operates in discontinuous condition mode (DCM). Both the MOSFETs turning ON and the diodes turning OFF occur at zero current, which reduces the switching loss remarkably. Further details of this bridgeless converter can be found in [5].

C. MPP tracking

The pursuit of maximum power harvesting is essential for the energy harvesting system to achieve a long operation time. The basic idea is to implement MPP tracking using impedance...
matching. In order to simplify the analysis of MPPT, some assumptions are made during one switching cycle.

1) Output filter capacitance C is sufficiently large to keep the output voltage $V_o$ constant with ignorable ripple.
2) The voltage of input filter capacitor is considered as an ideal sinusoidal voltage source. This voltage source serves as the input of the ac terminal of the PEI. The switching frequency is much higher than the frequency of the voltage source. Therefore, in every switching period, the input voltage can be considered as a DC voltage. The voltage is expressed as (3).
3) All components are considered as ideal with ignorable power losses.

The key waveforms are shown in Fig. 3. In the time period $d_1 T_s$, current of inductor $L_1$ increases linearly. Thus, the peak value of input current can be expressed as (4)

$$i_{pk}(t) = d_1 T_s v_{c_1}(t)/L_1$$

According to inductor volt-second balance

$$v_{c_1}(t)d_1 T_s = (V_o - v_{c_1}(t))d_2 T_s$$

The average power over a switching period is derived as:

$$p(t) = \frac{v_{c_1}(t)i_{pk}(t)(d_1 + d_2)}{2}$$

The input energy of the positive half cycle is derived as:

$$E_{in} = \int_0^{T_{in}/2} \frac{v_{c_1}(t)i_{pk}(t)(d_1 + d_2)}{2} dt$$

According to (3)-(7)

$$E_{in} = \int_0^{T_{in}/2} \frac{v_{c_1}(t)i_{pk}(t)(d_1 + d_2)}{2} dt$$

It should be noted that the output voltage of the microscale EH is typically below 0.5 V while most electronic loads should be driven by a 3.3 V voltage. This means the output voltage is much higher than input voltage. Therefore, the input energy can be approximated to zero. Thus, the total input power through the rectifier can be derived as:

$$E_{in} \approx V_{c_1}^2 T_s d_1^2 T_{in}/8 L_1$$

Without considering the conducting loss and switching loss, the average input power during positive half-cycle is equal to that of negative half cycle. Therefore, the average input power can be derived as:

$$\langle P_{in} \rangle = \frac{E_{in}}{T_{in}/2} = V_{c_1}^2 T_s d_1^2 /4 L_1$$

Thus, the equivalent input resistance of the bridgeless rectifier $R_e$ can be derived as

$$R_e = 2 L_1/d_1^2 T_s$$

It should be noted that its input impedance $R_e$ is only related to the duty cycle of the main switch and $L_1$. Moreover, the load ($R_o$) and the bi-directional dc/dc converter have no impact on $R_e$. Therefore, MPP tracking can be fully decoupled with voltage regulation. Once the converter is selected, the input impedance can be regulated by the duty cycle of the main switch. As shown in Fig. 4, when the input impedance is equal to the equivalent source impedance of the micro-generator, the maximum power can be harvested.

**D. Power flowing analysis**

In the topology, the bridgeless rectifier and the bi-directional buck/boost converter cascade together with a dc link. The bridgeless rectifier operates in DCM and the bi-directional buck/boost converter operates in CCM. When the voltages of both inputs are assumed constant and only the duty cycles are adjusted, based on voltage-second balance:

$$v_{c_1}(t)d_1 T_s = (V_o - v_{c_1}(t))d_2 T_s$$

At steady state, the output voltage is only dependent on the duty cycle of bi-directional buck/boost stage $d_3$. Thus, in this circuit, the duty cycle of the bridgeless rectifier is utilized to track MPP, while the duty cycle of bi-directional buck/boost converter is utilized to regulate the output voltage. The output voltage can be better controlled with smaller ripple compared to the traditional two-port ac/dc converters due to the battery voltage is more stable than the micro-generator terminal voltage.

When the maximum power is harvested from the EH, the input power of bridgeless rectifier can be expressed as:

$$P_{in} = \frac{(V_{in})^2}{2 R_e} = \frac{V_{in}^2}{8 R_e}$$

When the loss of the converter is ignored, according to the law of energy conservation:

$$P_{in} + \langle i_{L2} \rangle V_b = \frac{V_o^2}{R_o}$$

According to (14) and (15),

$$\langle i_{L2} \rangle = \frac{V_o^2}{R_o V_b} - \frac{V_{in}^2}{8 V_b Z_{lin}}$$

Since the load side power is constant and the voltage of the battery is almost unchanged, MPP can be tracked by monitoring the average current of the $L_2$.

Based on this relationship between the power generation from the micro-generator and the power demand from the load, three possible scenarios may occur. The power flow diagrams are demonstrated in Fig. 5.

1) Scenario I, when the power generation is matched to power demand, i.e. $P_{in} = P_o$; the battery doesn’t
exchange power in an average period. Indeed, this case rarely happens.

2) Scenario II, when the power generation is higher than the power demand, i.e., \( P_{in} > P_o \); the battery absorbs the extra power generated by the generator. The battery is charged.

3) Scenario III, when the power of micro-generator is not enough to supply the load, i.e., \( P_{in} < P_o \); the battery provides redundant power to the load. The battery is discharged.

4) Scenario IV, when the ac/dc side doesn’t work, only the bi-directional dc/dc converter supplies power to the load. In this case, \( P_b = P_o \).

### III. DESIGN GUIDELINE

In this section, design guidelines for the power converter and the controller are presented. The converter has to be designed in such a way that they can offer an optimal load to the energy harvesting source.

The power stage needs to be designed to offer a matched impedance with the energy harvesting source(s). The ac/dc converter is designed to boost hundreds of millivolts ac voltage to a high dc voltage (3.3 V). The switching frequency \( f_s \) of the converter is selected to be 50 kHz.

In the experiment, a power amplifier is utilized as the ac input source whose amplitude is 0.8 V and frequency is 100 Hz. The internal impedance is emulated by the internal resistance of the power amplifier which is 1 \( \Omega \). A bulky capacitor \( C_1 \) is utilized as the EMI filter in the input port. The high-frequency current component is absorbed. Therefore, the power factor is improved.

The rectifier should also be guaranteed to operate in DCM, which makes the output voltage not influenced by the rectifier stage. What’s more, it’s also beneficial to achieve the ZVS turning on of \( S_1, S_2 \) and the zero-current-switching (ZCS) turning off of \( D_1, D_2 \), both contribute to reduced switchin loss. Thus, based on the volt-second balance, the following equations can be derived:

\[
d_2 = d_1 \frac{v_{c1}}{V_o - v_{c1}}
\]

At the MPP,

\[
Z_{in} = R_e = \frac{2L_1}{d_1^2 T_s}
\]

Thus, the duty cycle can be expressed as follows:

\[
d_1 = \sqrt{\frac{2L_1}{R_e T_s}}
\]

In DCM, the following relationship should be satisfied.

\[
d_1 + d_2 < 1
\]

Based on (17-20), \( L_1 \) can be expressed as follows:

\[
L_1 < \frac{Z_{in} T_s}{2} \left( \frac{V_o}{v_{c1}} \right)^2
\]

Thus, the upper limit can be calculated when \( v_{c1} \) is at its peak value.

As derived in (11), the input impedance of the rectifier depends on the duty cycle and \( L_1 \). The curves of impedance versus duty cycle with different inductances are plotted in Fig. 6. It is shown that the input impedance decreases with the increase of duty cycle. In a practical converter, the duty cycle is generally limited within 0.2 - 0.9. The design of the converter and the selection of \( L_1 \) depend on the characteristics of the micro-generator based on the profiles in Fig. 6. The impedance match can be achieved by experimental verification. Based on these results and the limitation expressed in (21), the appropriate \( L_1 \) can be selected so that the required impedance falls into the normal operation range. The designed parameters are summarized in Table I. \( L_1 \) is selected to be 3 \( \mu \)H. Thus, the input resistance can be adjusted over a wide range from 0.4 \( \Omega \) to 7.5 \( \Omega \), which corresponds to a duty cycle range from 0.2 to 0.9. It should be noted that this resistance range is sufficient as it is wider than the internal impedance variation range of EH.

As for the bi-directional dc/dc converter, in order to realize ZVS, a negative current of \( i_{L2} \) is required. As shown in Fig.
2, when only the bi-directional provides the power to the load, the average current of \( L_2 \) reaches its peak value. While the smallest negative current occurs. To ensure a secure ZVS, following equation should be satisfied.

\[
\frac{\Delta i_{L2}}{2} > \langle i_{L2} \rangle \tag{22}
\]

\( \langle i_{L2} \rangle \) can be expressed as follows according to power conservation.

\[
\langle i_{L2} \rangle = \frac{V_o^2}{R_o V_b} \tag{23}
\]

\[
\Delta i_{L2} = \frac{V_b (1 - d_3) T_s}{L_2} \tag{24}
\]

According to (22)-(24),

\[
L_2 < \frac{V_o^2 (1 - d_3) R_o T_s}{2 V_b^2} \tag{25}
\]

Larger inductance corresponds to smaller RMS current, which is beneficial to the reduction of conduction loss. To limit the inductor volume and to reverse sufficient ZVS margin, \( L_2 \) is selected to be 100 \( \mu \)H.

The simplified control scheme is illustrated in Fig. 7. The operations of \( S_1 \) and \( S_2 \) are different in positive and negative half cycles. Hence, a polarity detector is needed to detect the voltage polarity, as depicted in Fig. 7. DSP TMS320F28379D is employed as the micro-controller. Due to the battery voltage varies with the battery state-of-charge, a closed-loop control with negative feedback is adopted to regulate the output voltage. The output voltage is fed to the analog-to-digital converter(ADC) of the digital controller by going through a low pass filter as shown in Fig. 7. The main electronic component models are shown in Table II.

### IV. Hardware Implementation

The small-signal circuit model can be obtained by modeling the bi-directional buck/boost converter. Indeed, it is identical to the state-space averaging model of classic buck/boost topology [12]. Its control-to-output transfer function is derived as follows:

\[
\frac{v_o(s)}{d(s)} = \frac{D V_b (1 - s L)}{C \Omega^2 R_o + L^2 s^2 + \frac{L}{R_o} s + D^2} \tag{26}
\]

A digital PI algorithm is implemented in the control loop based on the small-signal model of the converter.

The MMP of rectifier is tracked by monitoring the average current of \( L_2 \) in an open-loop manner. The smaller the average value is, the higher power is harvested from rectifier.

### V. Experimental Results

A 10 mW rated converter prototype, which processes the power from among a 0.6 V, 100 Hz, ac source, a 1.2 V battery, and a 3.3 V constant voltage load is developed and tested. Experiments are conducted to verify the effectiveness of the proposed concept. The ratings of selected components are shown in Table I.

Due to the output voltage is controlled by bi-directional dc/dc converter, an open-loop experiment is conducted to track the MMP by monitoring the average current of \( L_2 \). The experimental data is recorded in Fig. 8. The blue curve demonstrates the relationship between duty cycle and the average current of \( L_2 \). The red curve represents the average battery power which equals the average current of \( L_2 \) multiplied by the battery voltage \( V_b \). The average current of \( L_2 \) reaches the valley value when the duty cycle of \( d_1 \) is adjusted to be 0.42. Thus, the battery power is at its valley. Based on (15), the maximum power of ac/dc rectifier stage can be harvested in this scenario.

Fig. 9 shows the experimental waveforms of the polarity detection and the driving signal of \( S_1 \) and \( S_2 \). Fig. 10 shows the experimental waveforms of the rectifier stage. The inductor current envelop is synchronized with the steady state input voltage. The output voltage has small voltage ripple. The
Fig. 8. Open-loop plot of power and average battery current versus duty cycle $d_1$.

Fig. 9. Experimental waveforms of the bridgeless rectifier.

Fig. 10. Experimental waveforms of the three-port converter.

Fig. 11. Experimental waveforms of the bi-directional dc/dc converter.

The detailed theoretical analyses of the proposed circuit are provided and the design considerations are addressed. The design guidelines are provided to optimize the converter parameters. The experimental results of MPPT, ZVS and three-port converter are presented to validate the concept.

VI. CONCLUSION

In this paper, a three-port power electronic interface is proposed for low voltage energy harvesting systems. It contains a bridgeless rectifier and a bidirectional buck/boost converter that connects a rechargeable battery. The topology has the following advantages:

1) maximum power of micro-generator is harvested;
2) the output voltage is always well regulated in different operation scenarios;
3) a battery is applied to buffer the redundant energy;
4) all switches can achieve soft switching with reduced switching loss.

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