An Efficient Direct AC-DC Converter for Low Voltage Energy Harvesting System

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Abstract: **The traditionally established two-stage power converters with rectifiers are inefficient and may not be practical for the low-voltage piezoelectric generators electromagnetic generators. In this paper, a single-stage ac–dc power electronic converter is proposed that avoids the bridge rectification, dc-dc converter and directly converts the low ac input voltage to the required high dc output voltage at a higher efficiency. The topology combines a buck-boost dc-dc converter and a boost dc-dc converter to condition the positive and negative half portions of the input ac voltage, respectively. Only one inductor and split filtering capacitor are used in both circuitries to reduce the size of the converter control schemes are proposed to operate the converter. The AC input voltage with amplitude less than 1V is rectified and stepped up to DC voltage of 3.3V. Such a single stage ac-dc converter simulated using MATLAB/SIMULINK at 50-kHz switching frequency.**

Keywords/Index Terms **— AC/DC conversion, boost, bridgeless, buck-boost, energy harvesting, low- voltage rectification, power converter control.**

1. INTRODUCTION

Energy harvesting refers to capturing energy available in the environment and converting it to a useful form of energy such as electricity. Current forms of energy harvesting employ wind, solar, mechanical/vibration, thermal, and radio waves. In several ways all these energies can be harvested. Vibration energy harvesting technology has become a promising power supply solution for applications requiring microwatts to milliwatts of power. Combined with improved energy conversion techniques, several energy harvesting solutions have started to become feasible. A complete energy harvesting solution obviously requires the harvester for mechanical to electrical energy conversion. Typically, kinetic energy is converted into electrical energy using piezoelectric generator.

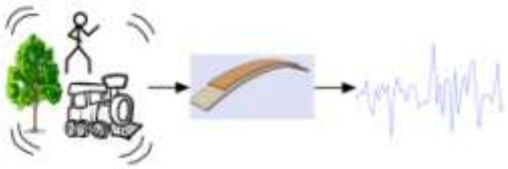


Figure 1: Vibrational energy is apparent everywhere. One method to harvest the Vibrational energy is to mount a piezoelectric material in the vibrating environment. During motion, the piezoelectric material will generate an AC voltage.

The output AC voltage amplitude of the piezoelectric material is dependent on the mechanical setup and the vibration amplitude and frequency and can be from 0 V to > 50 V. The vibration level explored in this project is however low, and the focus is on voltages around 0.4V.

In energy harvesting systems, power electronic circuit forms the key interface between transducer and electronic load, which might include a battery. In the harvesting system a compact and highly efficient power management circuit is as important. A complete energy harvesting solution obviously requires the harvester for mechanical to electrical energy conversion, but also application specific power management circuitry to perform ac/dc rectification, voltage/current boost, voltage/current regulation, and other power management functions. Traditional ac–dc converters for energy harvesting and conditioning usually consists of two stages. A diode bridge rectifier typically forms the first stage, while the second stage is a dc–dc converter to regulate the rectified ac voltage to a dc voltage (in Fig. 2).

The arrangement of two stage power conversion has several disadvantages:

1. Diode voltages in a bridge rectifier are difficult to overcome for low input voltage.
2. Diode losses are increased, as input current is much higher than output current.

3. Nonlinear load is offered by rectifier, which makes the converter unsuitable for energy harvesting.

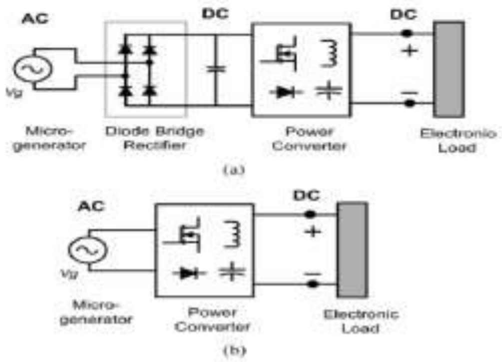


Figure 2: Block diagrams. (a) Conventional two stage power conversion consisting diode bridge rectifier. (b) Direct ac-to-dc power conversion

Another approach to maximize the conversion efficiency in low-voltage rectification is to use bridgeless direct ac–dc converter. The boost converter is the common power conditioning interface due to its simple structure, voltage step-up capability, and high efficiency. The buck-boost dc-dc converter having the capability of stepping up of input voltage with a reverse polarity. Beside the boost and buck – boost topologies, it could share the single inductor and capacitor to meet the miniature size and weight requirements.

1.1. SINGLE STAGE DIRECT AC-DC CONVERTER

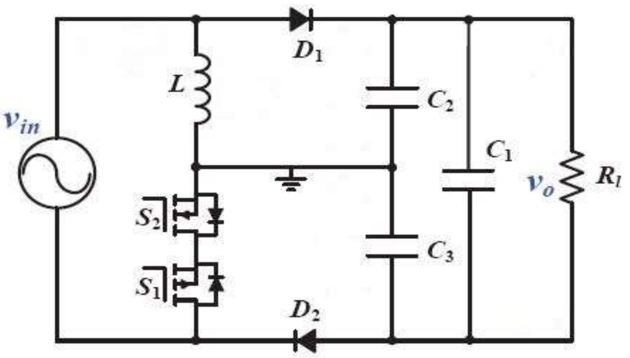


Figure 3: Direct AC-DC Converter for low-voltage energy harvesting.

A direct ac-dc converter, shown in Fig. 3, which is a combination of boost and buck-boost dc-dc converters, is presented in this paper. When*S*1 is turned ON, the input voltage is positive and *D*1 is reverse biased. In this condition the circuit operates in the boost mode. As soon as the input voltage becomes negative, the buck- boost mode starts with turning ON *S*2 and reverse biasing *D*2. To ensure the circuitry functionality in both positive and negative voltage cycles the MOSFETs with bidirectional conduction have capability to work as two-quadrant switches. The circuit operation modes are described in Section 2. In Section 3, switching sequence of the ac-dc converter .In section 4, the design procedures and guidelines are discussed. Section 5, explains the simulation results. Section 6, presents the conclusions.

2. PRINCIPLE OFOPERATION

To supply constant voltage and power to the load is done using power electronics interface (PEI). In order to facilitate or simplify the circuit analyses, it is assumed that the input impedance of the PEI is significantly more than the internal impedance of energy harvesting device. Low amplitude sinusoidal AC voltage source is assumed as induced voltage. In this paper, a 0.4-V, 100-Hz sinusoidal ac voltage source is adopted to emulate the output of the energy harvester.

The DCM operating modes of the direct AC/DC Converter are shown in Fig. 4. Each cycle of the input ac voltage can be divided into three operating modes. For positive half three modes and for negative half cycle three modes. Modes I–III illustrate the circuit operation during positive input cycle, where *S*1 is turned ON while *D*1 is reverse biased. The converter operates as a boost circuit for the first three modes, while switching *S*2 and *D*2.The operation during negative half cycle is demonstrated in Modes IV–VI, where *S*2 is turned ON while *D*2 is reverses biased. In these modes, the converter operates similar to a buck-boost circuit.

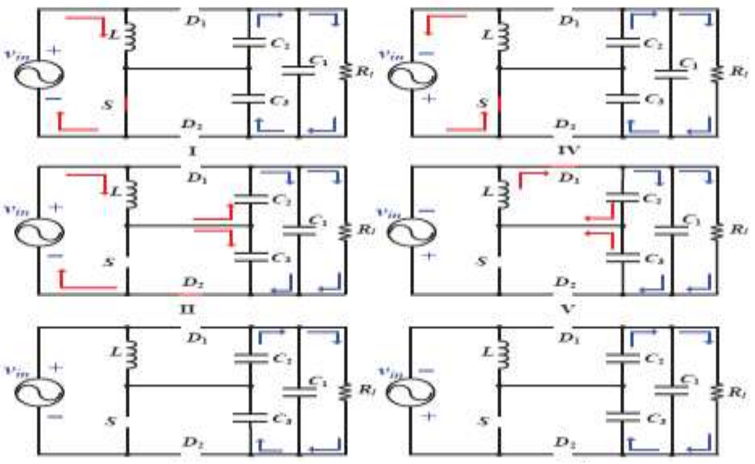


Figure 4: Operating modes of the proposed converter.

Mode I: This mode begins when switch S2 is turned ON at initial time t0. The inductor current is zero at t0. The zero current switching (ZCS) is achieved when the switch S2 is turned ON in to reduce switching loss. When switches S1 and S2 are conducting the inductor L is energized by the input voltage. Both diodes are reverse biased. The load is powered by the energy stored in the output filter capacitor C.

Mode II: At t1, the switch S2 is turned OFF, where t1 − t0 = d1Ts, d1 is the duty cycle of the boost operation, and T s is the switching period. The energy stored in the shared inductor L during first mode is transferred to the load. The inductor current decreases linearly. During this mode, switching loss occurs during the turn on of diode D2.

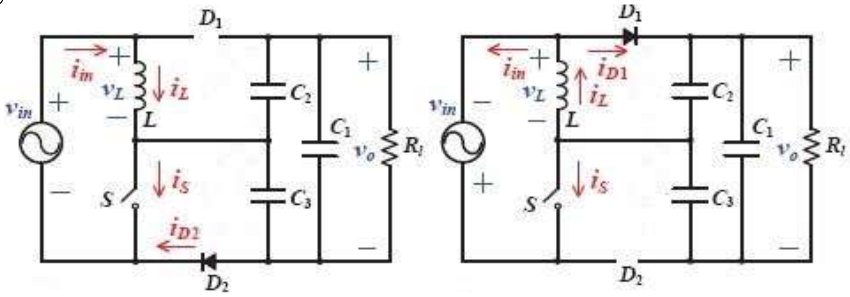
Mode III: Diode D2 is automatically get reverse biased as soon as the inductor current becomes zero at t2 (t2 − t1 = d2Ts). This avoids the reverse recovery loss of diode. The power to the load is supplied by the energy stored capacitor. The converter would return to Mode I as soon as S2 is turned ON, if the input voltage is still in positive cycle.

Mode IV: During the negative input cycle, Mode IV starts as soon as S1 is turned ON at t_0. If the converter operates in DCM, ZCS condition can be achieved. The energy is transferred to the shared inductor L again, while the output filter capacitor C3 feeds the load.

Mode V: At t_1, S1 is turned OFF, where t_1 − t_0 = d_1 T s, d_1 is the duty cycle of the buck-boost operation. The energy stored in the inductor during Mode IV is transferred to the load. The inductor current decreases linearly. During this mode, switching loss occurs during the turn on of the diode D1.

Mode VI: When the inductor current decreases to zero at t_2 (t_2 − t_1 = d_2Ts), D1 is turned OFF at zero current. The load is continuously powered by the charge stored in the output filter capacitor C3. When S1 is turned ON, the converter would return to Mode IV, if the input voltage is still negative.

According to the operation modes of the circuit, with ZCS the switches will be ON and the diodes will be OFF. The input current sensor can be eliminated in the DCM operation .In the control scheme of DCM operation; the switching loss can be reduced. DCM operation is more suitable than continuous conduction mode (CCM) operation due to the circuit size can be reduced and the efficiency can be enhanced.



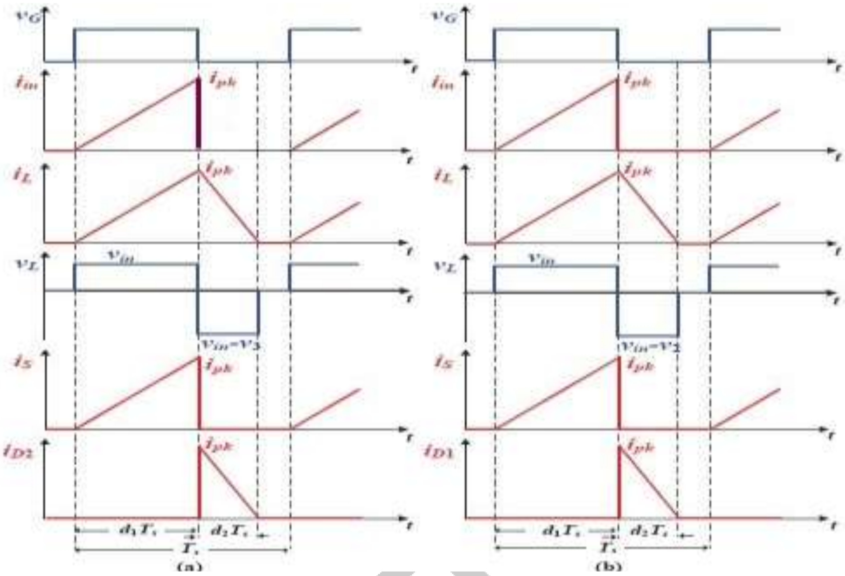


Figure 5: Waveforms of the proposed direct ac-dc converter. (a) Boost operation. (b) Buck-boost operation.

3. DESIGN PROCEDURE OF AC/DCCONVERTER

The commutation relationship of the duty cycle of the proposed converter as shown in below equation [1],

$$D = d_1 = d_1^1 = \frac{2Vo}{v_m}\sqrt{\frac{Lfs}{R}} \text{.......................} \quad (1)$$

According to the specific application, the boost ratio is defined and the load resistance R is dependent on the output power level. The inductor is designed with the specified power and voltage demands according to the desired range of duty cycle and switching frequency. The inductance will be smaller if the switching frequency larger. A higher switching frequency is preferred in order to design a smaller inductor with purpose of obtaining smaller size and weight. The switching losses will be high if the switching frequency is high. A tradeoff between the switching loss and the size of inductor should be taken into account in the design process. Both the boost and buck-boost operations of the converter provide the same inductor current ripple, which can be expressed as,

$$\Delta i_L = \frac{v_{in}(t)DT_s}{L} \text{..........................} \quad (2)$$

The maximum current ripple gives peak input voltage. The inductor, diodes, and MOSFETs share the same value of current ripple, which is defined in the following equation:

$$\Delta i_{L,\,max} = \frac{v_m DT_s}{L} \text{..........................} \quad (3)$$

From (3), the current ratings of all those components could be found.

3. SWITCHINGSCHEME OF AC/DCCOVERTER

The AC/DC converter is tabulated as shown in Table 1. The switching is as per Figure 3

Table 1. AC/DC converter switching scheme

Time Period	**S2**	**S1**
Positive half cycle	Switching	ON
Negative half cycle	ON	Switching

During the positive input cycle, *S*1 will conduct, while *S*2 is driven by the boost control scheme with switching frequency, fs. When the circuit operates in the negative input cycle, *S*2 will conduct, while *S*1 is controlled under the buck-boost conditioning strategy with switching frequency, fs. Thus the circuit is implemented in boost and buck-boost mode. Switching logic is simulated using MATLAB/SIMULINK as shown.

Figure 6 shows the simulation model of gate signal generation. A constant is used to determine the input voltage polarity.

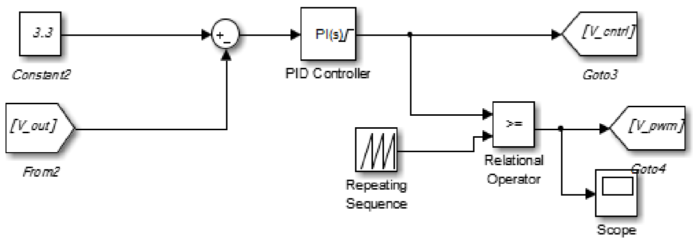


Figure 6*:* Simulation model of gate signal generation.

As per the fig.6, by comparing the relational operator with positive sign detector, the gate pulse will generate for switch1 and by comparing the relational operator with negative sign detector, the gate pulse will generate for switch2.

5. SIMULATIONRESULTS

The circuit components of AC/DC Converter are listed in the table 2

Table2:.Margin specifications

Input voltage	0.4V
Output voltage	3.3V
Inductor	4.7µH
Resistor	200Ω
Capacitors(C2 & C3)	47µF
Capacitor (C1)	100µF
Switching frequency	50kHz

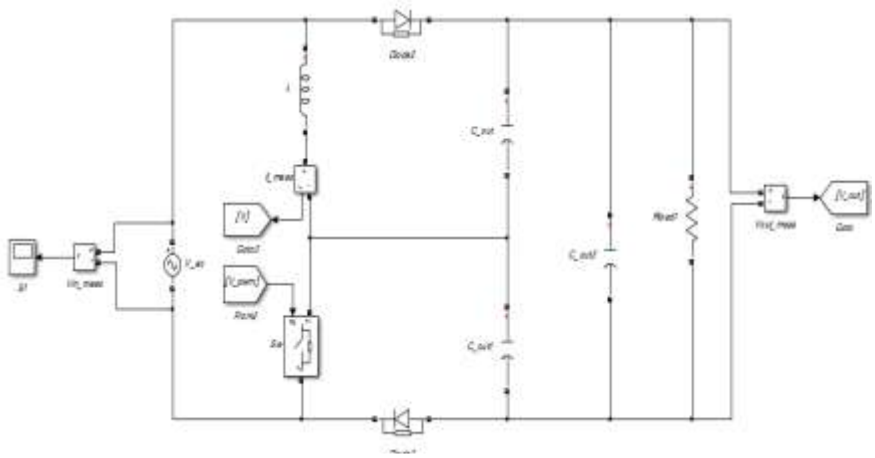


Figure 7: Simulation model of AC/DC Converter

Figure 7 show the AC/DC Converter was simulated using MATLAB/SIMULINK with input voltage 0.4V and output voltage of 3.3V. The topology combines a buck-boost converter and a boost converter to condition the positive and negative half portions of the input ac voltage, respectively. Only one inductor and split capacitor are used in both circuitries to reduce the size of the converter.

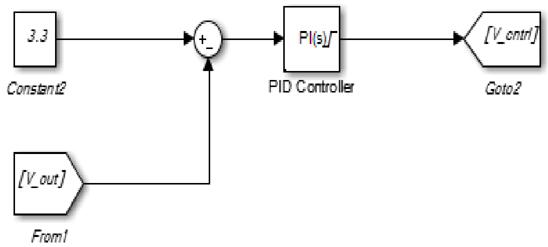


Figure 8: Simulation model of Controller Circuit

Figure 8 shows the AC/DC Converter controller circuit was simulated using MATLAB/SIMULINK. Closed-loop voltage control successfully stabilizes the duty cycle at 72% at the steady state. Gate pulses generated for S1 and S2 and output voltage waveforms of bridgeless boost rectifier as shown in below.

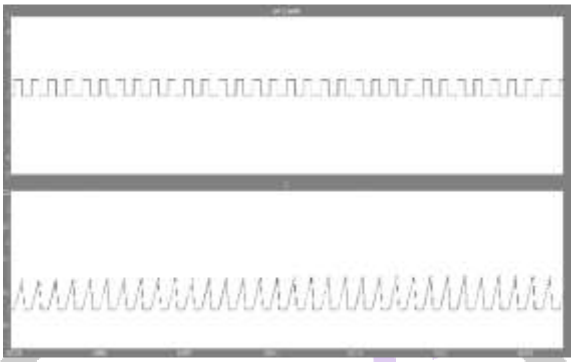


Figure 9: Gate pulses generated and inductor current

The Fig .9 shows the gate pulses and inductor current for AC/DC Converter during the positive half and negative half cycle, respectively. The switching signals of *S*1 and *S*2 depends on the polarity of the input voltage.

Figure 10 shows that regulated output voltage waveform. As seen from Fig. 10, the low ac input voltage is successfully boosted to a well-regulated higher dc output voltage (3.3 V).

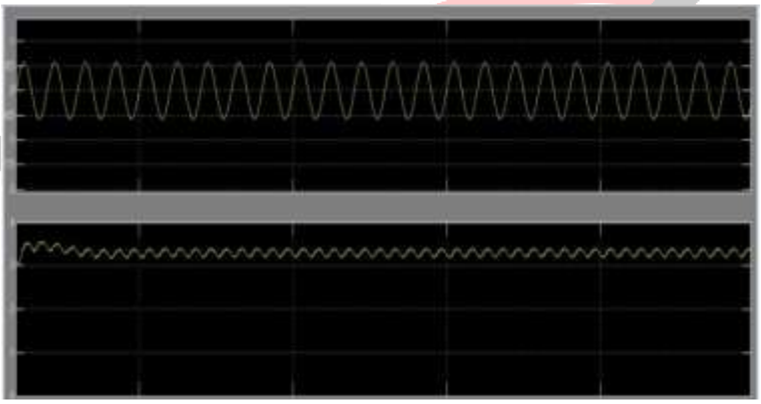


Figure 10: Input and Regulated output voltage waveform of AC/DC Converter with Vo=3.3v.

6. CONCLUSION

The bridgeless boost rectifier was simulated using MATLAB/SIMULINK. The topology combines a buck-boost dc-dc converter and a boost dc-dc converter to condition the positive and negative input cycles, respectively. Only one inductor and split filtering capacitors are required in this topology. The topology successfully boosts the 0.4V, 100Hz ac to 3.3Vdc. The output voltage regulated to 3.3V through closed loop voltage control. By comparing bridgeless rectifiers, this topology employs the single circuit and minimum number of passive energy storage components, and achieves the maximum conversion efficiency. The future research will be focused on investigating and designing for much more voltage for various other applications.

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