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A Comparative Study of Various AC-DC Converters for Low Voltage Energy Harvesting

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Abstract: **Electromagnetic microscale and mesoscale power generators with low voltage outputs are now widely used as kinetic energy harvesters. The extrinsic vibrations on the generator can excite the internal oscillations between the proof mass magnet and the electrical damper coils. These oscillations produce a periodically varying magnetic flux in coil, inducing a corresponding AC output voltage. This output can be converted to dc and can be used to supply power to electronic loads. The conventional AC-DC converters for energy harvesting system with diode rectifiers suffer considerable voltage drop resulting increase in power loss of circuitry and complexity. As a remedy various bridgeless boost converters were designed and implemented. Standard H bridge converter with 4 switch or 2 switch, dual polarity boost converters, parallel combination of boost and buck-boost converter, integrated boost and buck-boost combination bridgeless rectifier are some of these. These circuits are studied, simulated and compared. The simulation models are drawn and simulated using MATLAB R2010a.**

Keywords: **Low voltage energy harvesting, AC-DC conversion, Bridgeless, Buck, Buck-boost, Polarity detector, Zero current switching.**

I. INTRODUCTION

Mostly Mechanical energy present in the environment is converted to electrical energy using kinetic energy harvesters. Generally this is done with the help of electromagnetic transduction devices. Electromagnetic transducers outplay in terms of efficiency and power density. The exterior vibrations on the harvester excite the internal oscillation between the magnet and damper coils. This produce a periodically variable magnetic flux in the coil, which induces a corresponding alternating output voltage. For the purpose of energy harvesting, power electronic devices are accommodated between the transducer and the electronic load. These circuits are employed to regulate the power delivered to the load and actively manage the electrical damping of the transducers so that maximum power will be delivered to the load.

Various AC-DC converters have been designed and developed through the years for the purpose of low voltage conversion. An important drawback of the conventional AC-DC converter [1] is the significant voltage drop caused by the diode bridge. Therefore, this circuit is infeasible for low voltage rectification. In order to maximize the efficiency of the converter, bridgeless AC-DC converters were developed. Standard H-bridge 2 or 4 switch converters [2], dual polarity boost converter [3], parallel combination of DC-DC converters [4] and bridgeless buck-boost converter [5] are examples of converters using such topology. The boost converter has simple structure, voltage step-up capability, and high efficiency. The buck-boost converter has ability to step up the input voltage with a reverse polarity. Here, a comparative study of various AC-DC converters which are used for low voltage energy harvesting is done.

II. LOW VOLTAGE AC-DC RECTIFIERS FOR ENERGY HARVESTING

As discussed before, the energy harvesters act as a low amplitude sinusoidal AC voltage source. The various power electronic interfaces discussed here are dedicated to supply a constant voltage and deliver power to the load. The frequency of the vibration source, and hence that of the induced voltage, is usually less than 100 Hz. Here, a 0.4V, 100 Hz sinusoidal AC voltage source is taken as the output of the electromagnetic energy harvester.

A. Conventional Power Converters:

A conventional power converter has a two stage operation to provide rectification [1]. First stage is a diode bridge rectifier and second is a DC-DC converter. During the positive half cycle, the diodes D_1 and D_2 conduct and D_3 and D_4 conduct for negative half cycle. The DC voltage obtained is passed on to the DC-DC converter. This converter produces the required DC voltage for load. Fig. 1 shows the conventional AC-DC bridge rectifier. Since this circuit contains a bridge rectifier, it is not a feasible solution for the low voltage energy harvesting operation. The on state forward voltage drop of a diode is high when compared to the output of an electromagnetic micro generator.

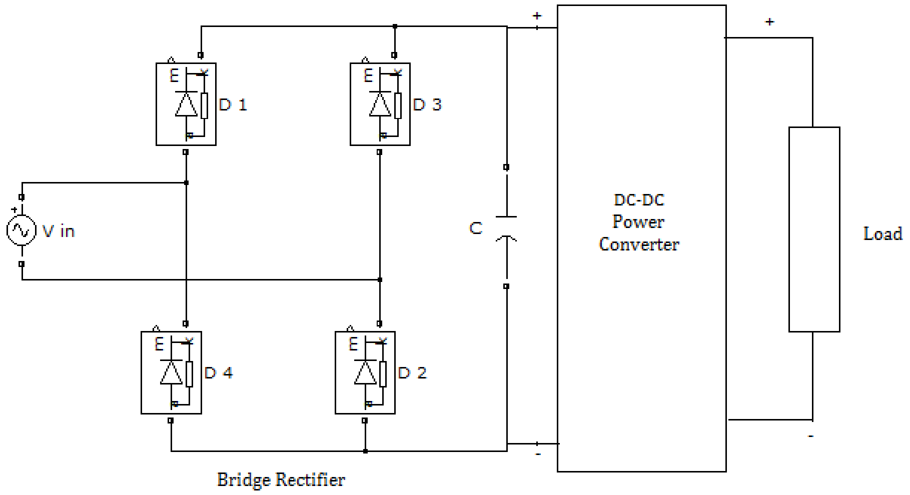
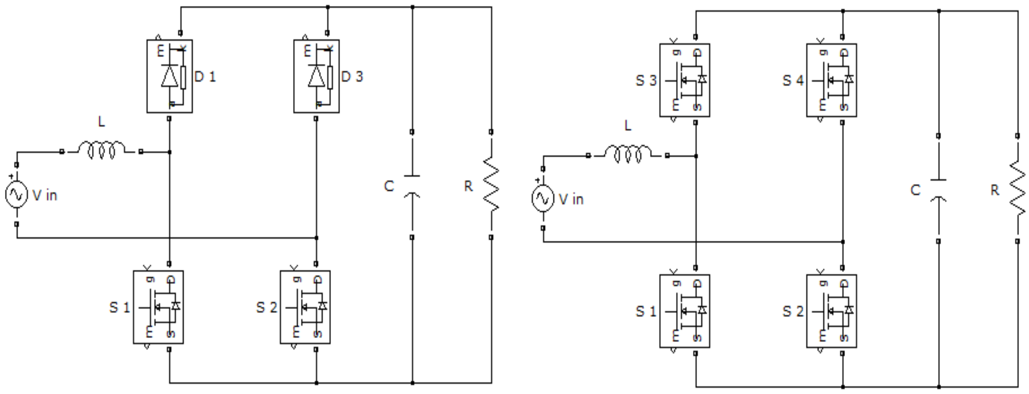


Fig.1. Conventional power converters

B. Standard 2 Switch/ 4 Switch H- bridge Converters:

In these converters, bridge rectification is avoided and is a single-stage power converter. Standard 2-switch/4-switch H-Bridge converters have direct AC-DC converter topology [2]. Fig. 2 shows the diagram of standard 2- switch and 4-switch H- bridge converters.



(a) (b)

Fig.2. (a) Standard 2-switch H-bridge converter, (b) Standard 4-switch H-bridge converter

The lower switches in the legs, S_1 and S_2, are MOSFETs with bidirectional conduction capability. During the positive half cycle, switch S_2 is kept ON for the entire half cycle and the gate pulse to S_1 is controlled to achieve the boost operation. Similarly, during the negative half cycle, S_1 is kept ON for the entire half cycle and the gate pulse to S_2 is controlled. The main demerit of the converter is that there are two devices present in the conduction path during the charging or discharging of the boost inductor. The second disadvantage is that it offers higher ON-state resistance.

C. Dual Polarity Boost Converter:

As a solution for the disadvantages of bridge rectifier, bridgeless AC-DC converter topologies were developed. The dual polarity boost converter process the positive and negative half cycles separately. Diode rectification is replaced by alternate stimulation of one of two voltage boost circuits [3]. Fig. 3 shows the two boost converter sub-circuits: one employed to produce the top half of the output voltage when the generator voltage is positive, and the other to produce the lower half, when the generator voltage is negative. The generator voltage is small that it is not able to forward bias the parasitic diodes in the MOSFETS. Synchronous rectification has been employed in the boost converter to avoid series connection of rectifier and boost stages.

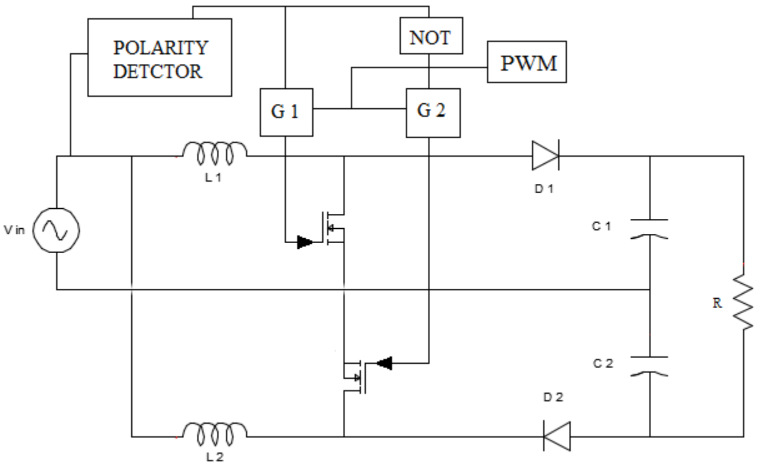


Fig.3. Dual polarity boost converter

D. Parallel Combination of Boost and Buck-boost Converter:

The circuit topology consists of a boost converter in parallel with a buck-boost converter. Each portion of this circuit has got its own diode, inductor and a switch [4]. During the positive half cycle, the circuit is in the boost mode and during the negative half cycle it is in the buck-boost mode. Fig. 4 shows the diagram of the circuit.

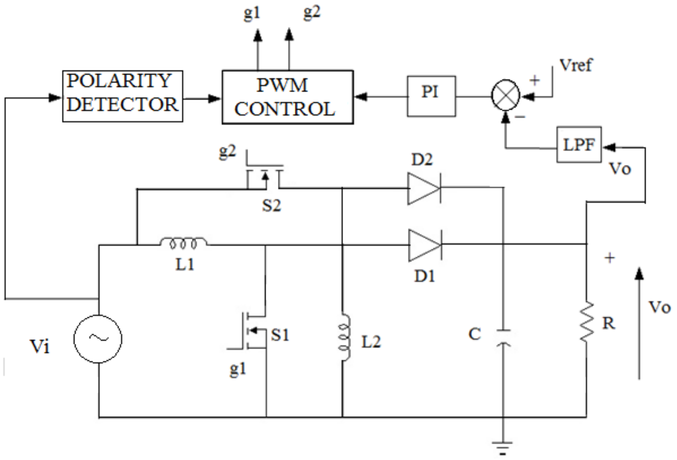


Fig.4. Parallel combination of boost and buck-boost converter

E. Integrated Bridgeless Boost Rectifier:

It is a unique integration of the boost and buck- boost converters. When the input voltage is positive, the circuit operates in the boost mode. S_1 is ON and D_1 is reverse biased during this interval. Similarly, when the input voltage is negative, S_2 is ON and D_2 is reverse biased for buck-boost operation. The circuit employs MOSFETs with bidirectional conduction capability. Both boost and buck-boost topologies could share the same inductor and capacitor [5].

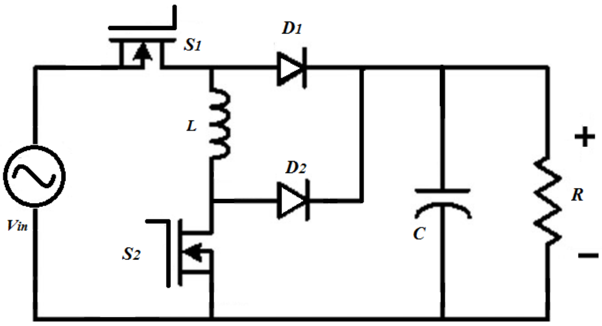


Fig.5. Integrated bridgeless boost rectifier

Mode I ($t_0 – t_1$): At t_0 the switch S_2 is ON. The inductor current is zero at t_0. In order to reduce the switching losses, S_2 is turned ON by zero current switching (ZCS). During the time t_0 to t_1, the inductor L gets charged, as both S_1 and S_2 are conducting both diodes D_1 and D_2 are reverse biased. The load is powered by the stored energy in the capacitor. T_s is the switching period.

Mode II ($t_1 – t_2$): The switch S_2 is turned OFF at t_1. The energy stored in inductor during Mode I is now transferred to the load. The inductor current now decreases linearly. Switching loss occur during the turn ON of diode D_2.

Mode III ($t_2 – t_3$): As the inductor current become zero at t_2, D_2 will be automatically turned OFF. This will prevent the reverse recovery loss of the diode. During this interval, the load is again powered by the energy stored in the capacitor. After mode III, if the input voltage is still in the positive half cycle, the converter would return to the mode I.

Mode IV ($t_0^{'} – t_1^{'}$): At $t_0^{'}$, the switch S_1 is turned ON. Zero current switching is achieved by ensuring the DCM operation of the converter. The energy is now transferred to inductor L. The load is powered by the energy stored in the output filter capacitor C.

Mode V ($t_1^{'} – t_2^{'}$): $S_1^{'}$ is turned OFF at the instant $t_1^{'}$. During this period, the energy stored in the inductor is transferred to the load. The inductor current decreases linearly due to this. D_1 is forward biased during this mode and causing switching losses.

Mode VI ($t_2^{'} – t_3^{'}$): At the time $t_2^{'}$, when the inductor current reaches zero, diode D_1 is turned OFF. Zero current switching is thus achieved. The charge stored in the output capacitor is continuously supplying the load. The converter would return to Mode IV as soon as S_1 is turned ON, if the input voltage is still in negative half cycle.

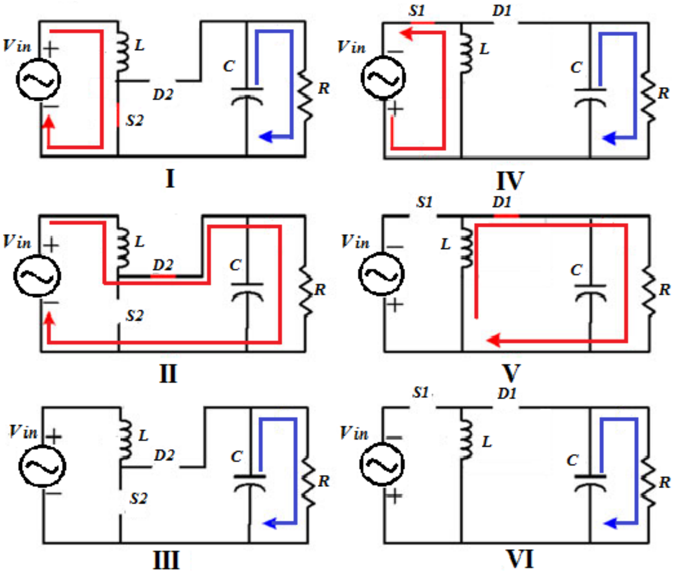


Fig.6. Operating modes of bridgeless boost rectifier

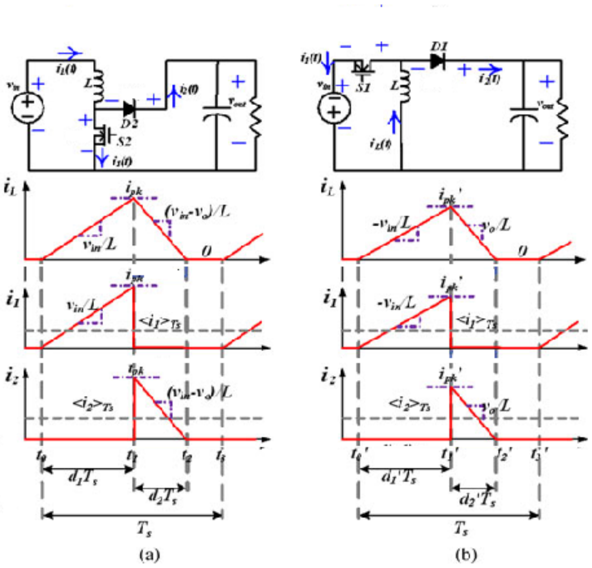


Fig.7. Waveforms during (a) Boost Operation, (b) Buck-boost Operation

III. SIMULATION RESULTS

The simulations were done on MATLAB/ Simulink. Tables 1-4 gives the simulation parameters of the various circuits discussed above.

Table 1. Simulation Parameters: H-bridge Converter

COMPONENTS	PARAMETERS
Input Voltage (V_{in})	0.4 V
Input Frequency	50 Hz
Switching Frequency f_s)	50 kHz
Inductor (L)	4.7 μH
Capacitor (C)	1 μF
Resistor (R)	100 Ω

Table 2. Simulation Parameters: Dual Polarity Boost Converter

COMPONENTS	PARAMETERS
Input Voltage (V_{in})	0.4 V
Input Frequency	50 Hz
Switching Frequency (f_s)	50 kHz
Inductors (L_1,L_2)	4.7 μH
Capacitors (C_1,C_2)	63 μF
Resistor (R)	100 Ω

Table 3. Simulation Parameters: Parallel Boost & Buck-boost Converter

COMPONENTS	PARAMETERS
Input Voltage (V_{in})	0.4 V
Input Frequency	50 Hz
Switching Frequency f_s)	50 kHz
Inductors (L_1,L_2)	4.7 μH
Capacitor (C)	63 μF
Resistor (R)	100 Ω

Table 4. Simulation Parameters: Integrated Bridgeless Boost Rectifier

COMPONENTS	PARAMETERS
Input Voltage (V_{in})	0.4 V
Input Frequency	50 Hz
Switching Frequency (f_s)	50 kHz
Inductor (L)	4.7 μH
Capacitor (C)	100 μF
Resistor (R)	200 Ω

With the above parameters the circuits were simulated, the output voltage and current waveforms were observed and the average output voltages were calculated. Figs. 8-11 show the output waveforms of the converters.

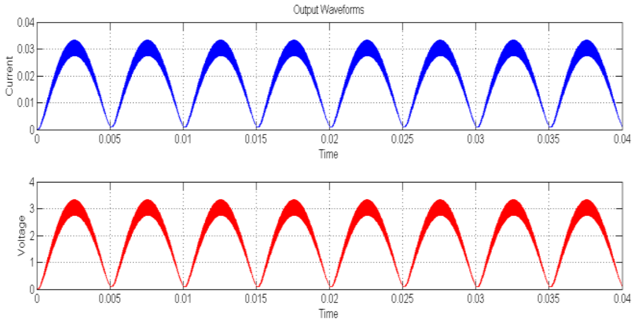


Fig.8. Output Waveforms: H –bridge

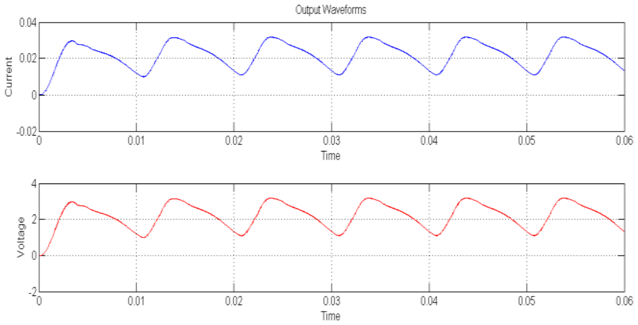


Fig.9. Output Waveforms: Dual Polarity Boost

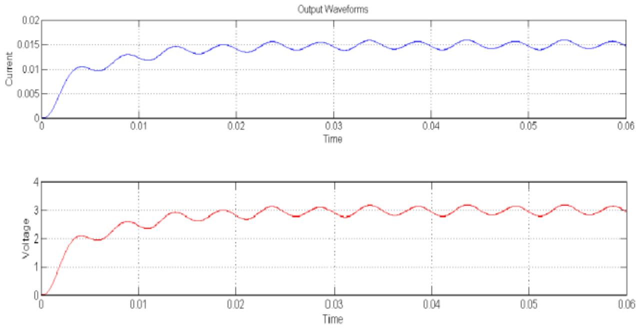


Fig.10. Output Waveforms: Parallel Boost & Buck-boost Converter

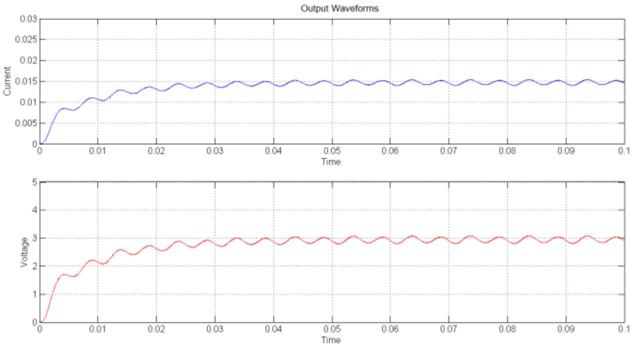


Fig. 11. Output Waveforms: Parallel Boost & Buck-boost Converter

Table 5 tabulates the average output voltage values of the different converters and corresponding boost ratios. It is derived from the output voltage waveforms obtained from the simulation.

Table.5. Comparison of average output voltages and boost ratios

CONVERTER	AVERAGE OUTPUT VOLTAGE	BOOST RATIO
H- Bridge Converter	1.02 V	2.55
Dual Polarity Boost Converter	2.20 V	5.50
Parallel Boost & Buck-boost Converter	2.90 V	7.25
Integrated Bridgeless Boost	3.00 V	7.50

It can be seen from the above table that the integrated bridgeless boost gives a higher value of average output voltage and hence more boost ratio. Also, it has an added advantage of lower number of passive components.

IV. CONCLUSION

AC-DC conversion for low voltage energy harvesting applications uses various power converters. Conventional bridge rectifiers are not feasible due to voltage drop across the diode. Due to this disadvantage of the bridge rectifiers, different bridgeless AC-DC converters were designed and implemented. They include standard H bridge converters, dual polarity boost converters, parallel combination of boost and buck-boost converters and bridgeless boost rectifier. Here, these various converters are studied, simulations are done and they are compared with each other. By simulating and comparing the different topologies, it can be concluded that the integrated boost rectifier is more efficient in case of voltage boost ratio. This rectifier needs only lower number of passive components compared to other converters due to the integration of boost and buck-boost converters.

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