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Low-Voltage Direct AC-DC Boost Converter for Microgenerator Based Energy Harvesting

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Abstract: The conventional power electronic converters used in the microgenerator based energy harvesting applications have two stages: a diode bridge rectifier and a dc-dc conveter. But it is less efficient and cant be used for electromagnetic microgenerators, as the diode bridge rectification is not normally feasible due to extreme low output voltage of the microgenerators. In this paper a direct ac-dc power electronic converter topology is proposed for efficient and maximum energy harvesting from low voltage microgenerators. The single stage ac-to-dc power conversion is achieved by utilizing the bidirectional conduction capability of MOSFETs. A suitable startup circuit,auxiliary dc supply circuit and a control circuit is proposed for the implementation of the converter.The proposed topology is simulated using LTspice and the results are presented to verify the operation of the converter and proposed auxilliary circuit.

Kywords: AC-DC power convesion, microgenerator, boostconverter, low voltage energy harvesting.

I. INTRODUCTION

Energy harvesting has recently attracted huge interest within both the academic community and in industry as a potential solution to powering Wireless Sensor Nodes(WSN), medical implants etc. . The development of energy efficient semiconductor devices has reduced the power requirements of electronic circuits. This has led to the development of self powered wireless electronic devices which harvest ambient energies like mechanical energy, thermal energy, light etc. ([1],[2]) .

Over last two decades researchers have developed various microgenerators using different conversion mechanisms and their associated electronics for energy harvesting ([3],[4]). Electromagnetic microgenerators are common among this as harnessing kinetic energy in the form of motion or vibration is generally the most versatile and ubiquitous ambient energy source available. It can also provide a good power density and thus is the most suitable for harvesting.Thermal devices require a temperature gradient inorder to generate electrical energy, and this is difficult to acheive over the small distances available in miniature generators. Solar devices can acheive relatively high power densities in good light conditions, but they are unsuitable for implantable devices or other low light situations.

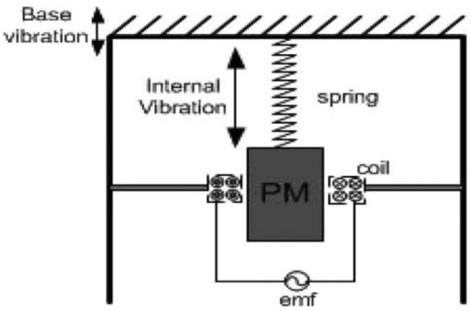

Fig. 1 Resonance based inertial electromagnetic microgenerator.

Electromagnetic generators are typically spring-mass systems , in which mechanical energy is converted to electrical energy by electromagnetic damping(Fig.1). The output of an inertial microgenerator is typically around a few hundred millivolts of ac. The power level of reported electromechanical microgenerators is very low, ranging from few microwatts to tens of milliwatts. Most of these inertial microgenerators are based on resonant spring-mass system, which enables higher amplitude oscillation of the mass for any low amplitude excitation.

It is unlikely that the transducer of a micro-generator will produce an electrical output in a suitable form for directly driving load electronics. Likewise, the electrical load does not necessarily present the transducer with the optimal electrical load characteristic for electrical energy generation. Consequently a power processing stage is necessary between the transducer and the load. Additionally,stored energy may be required to run the load electronics when the transducer is not generating.

The output of an inertial microgenerator, irrespective of its type, is an ac quantity. Hence, the micro-generator output has to be processed by a power converter to produce a suitable dc output voltage to meet the requirements of the end application. Moreover, in a microgenerator the amount of energy conversion depends on the damping force acting on the microgenerator . For maximum energy harvesting, the damper characteristics should be controlled to produce the optimal damping force. The damping force in an electromagnetic generator can be varied by changing the effective resistance connected to the output of the microgenerator. Power converters can be controlled to offer that optimum damping resistance.

A direct ac-dc boost convertor with split capacitor topology is discussed in this paper. It utilizes an n- and p-MOSFET pair to form the bidirectional switch which does not need floating gate drivers. A startup circuit, auxiliary dc supply circuit and a simple control strategy for energy harvesting and output voltage regulation is presented. The simulation results of the proposed converter are included to verify the operation of the converter and gate drive circuits.

II. REVIEW OF CONVERETER TOPOLOGIES

A power converter is required for energy-harvesting applications. The main function of the converter is to condition the ac output of the microgenerator to a suitable dc level and offer an adjustive resistive load to the microgenerator.

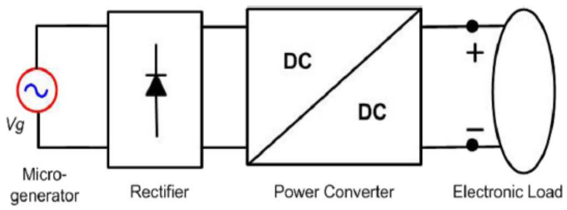

Fig. 2 Block diagram of two stage power conversion.

The conventional power converter for vibrational energy harvesting with two stage power conversion is shown in Fig. 4. It consist of a front-end diode bridge rectifier followed by a standard buck or boost converter ([5], [6]). This arrangement of two stage power conversion has several disadvantages for electromagnetic microgenerator:

a) Diode voltages in a bridge rectifier are difficult to overcome for low input voltage.
b) Diode losses are increased , as input current is much higher than output current.
c) A rectifier offers a nonlinear load , which makes the converter unsuitable for energy harvesting.

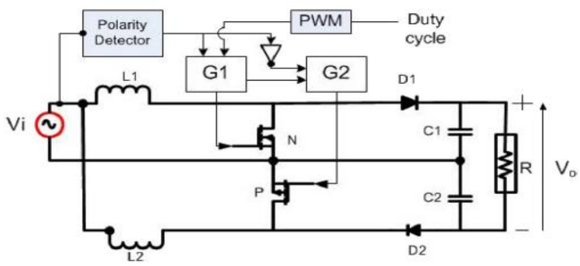

Fig. 3 Reported dual polarity boost converter.

Due to the above disadvantages two stage power conversion is not used for electromagnetic microgenerator based energy harvesting applications. The above disadvantages can be eliminated with the help of direct ac-dc boost converters. A dual polarity boost converter for direct ac-dc conversion is shown in Fig. 3. It uses two inductors, and the output dc bus is split into two series connected capacitors. It consists of two boost converters each operating in one half cycle of the ac voltage. Each capacitor is charged only in the respective half cycle. However, they discharge to load ,

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continuously causing large voltage drops. Extremely large capacitors are needed to make the voltage ripple acceptable. This makes the converter response very slow. The control of the converter also require input line polarity sensing which makes the circuit more complex.

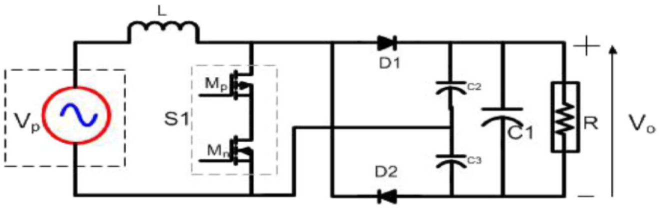

Fig. 4 Proposed direct ac-dc converter :split-capacitor topology.

The circuit diagram for split capacitor topology is shown in Fig. 4 [7]. A single inductor L is used for boost operation in both half cycles.The converter utilizes three capacitors to boost the low ac voltage. Here the bidirectional current conduction and blocking capability of MOSFET is used to form a bidirectional switch. Hence it is clear that the front-end bridge rectifier is replaced by the bidirectional switch for single stage power conversion. The bidirectional switch is realized by connecting drain of an n-MOSFET to the source of a p-MOSFET so that their body diodes block the current in the opposite direction.The gate signals are given to the MOSFETS simulaneously so that they are turned on and off at the same instants and thus can conduct and block current in both directions. The bidirectional switch is shown as S1 in Fig.4. Here the converter is operated in discontinuous conduction mode (DCM). This operation has many advantages:

a) A constant duty cycle extracts constant power from source , enabling a simple control.
b) A converter operating with a constant duty cycle has only fundamental and switching harmonic frequency components and thus offers a resistive load to the microgenerator.
c) DCM operation reduces switching losses which are significant in low power applications.

The spilt capacitors, C2 & C3, are charged and discharged by the inductor, L, in the positive and negative half cycles of the input voltage and they recycle the inductor energy to the output.

During the positive half cycle the inductor current increases linearly from zero when switch S1 turns ON. When S1 is turned OFF, the body diodes block the circulating current. Diode D1 is forward biased, and the current flows into capacitor C2 to complete the charging process.

In the negative half cycle, the current rises in the opposite direction when S1 is turned ON. However, this time, when S1 is turned OFF, diode D1 remains OFF and diode D2 is forward biased. The inductor energy is transferred to capacitor C3.

The three capacitors share energy through charge recycling. It should be noted that even though voltages across capacitors C2 and C3 show large variations, the duty cycle can be effectively controlled to maintain a steady voltage across output capacitor C1.

III. CONVERTER IMPLEMENTATION

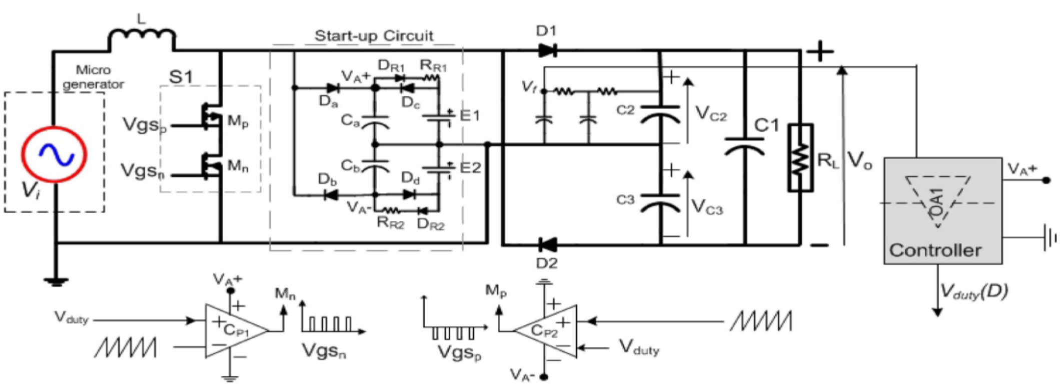

Fig. 5. Proposed direct ac-dc converter along with the auxiliary circuits.

The operation of the proposed direct ac-dc boost converter with split capacitor topology is discussed in section II . The implementation of auxiliary circuits (gate driver and control circuits) is very important for low power applications. They are chosen in such a way that they will consume very low power and they can be able to drive the

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circuit in steady state. In this section a gate driver circuit and an auxiliary dc supply with start up circuit are presented. A control strategy with its analog implementation is also described . The schematic of the power converter with the auxiliary circuits is shown in Fig. 5.

A. *Feedback and Control Circuit.*

From fig. 5 it is clear that the negative rail of the output voltage not the same as the ground of the control circuit which is the common node of the split capacitors. Therefore a specific feedback circuit for the converter has to be designed.

In split capacitor topology the two capacitors C2 and C3 have the same value. It is found that the average voltage across any of these capacitors is half of the output voltage. Therefore, this voltage can be used as feedback to the controller. However, due to charge recycling, the voltages across the split capacitors have designed to eliminate the voltage ripple and extract the dc large ac ripple. Two cascaded single pole low pass filters are designed to eliminate the voltage ripple and extract the DC voltage information (V_f).

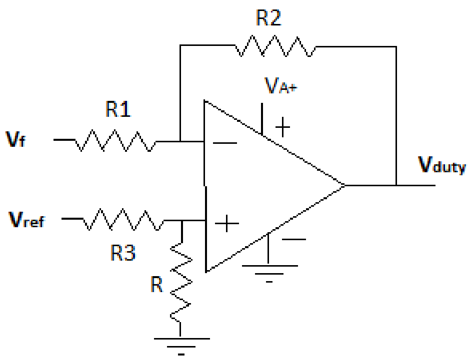

Fig. 6 Single op-amp based Proportional Controller.

A simple proportional controller is used to regulate output voltage to a nominal value of 3.3 V. Thus it can be used to charge rechargeable batteries for wireless and remote applications. A single op-amp in differential mode (Fig. 6) is used to implement the controller and the error amplifier. According to the normal gain in differential mode

$$V_{duty} = (R_2/R_1)(V_{ref}-V_f) \qquad (1)$$

B. *Gate Driver Circuit.*

The bidirectional switch S1 used in the converter is realized using an n-MOSFET (*Mn*) and a p-MOSFET (*Mp*) connected in series. The source of the n-MOSFET is connected to the ground. The source of the p-MOSFET is connected to the drain of the n-MOSFET. The bidirectional current conduction and blocking capability is obtained with the help of body diodes. In this converter, the MOSFETs are driven with respect to the common node of the split capacitors, i.e., C2 and C3.

Comparator *CP*1 is used to drive the n-MOSFET. Since the source of the n-MOSFET *Mn* is connected to the ground, it can be driven with a conventional low-side driver. Comparator *CP*2 is used to drive the p-MOSFET *Mp* using a negative gate pulse. It should be noted that the MOSFET*Mp* is driven with respect to ground instead of its source *Sp*. However, since the voltage drop across MOSFET *Mn* is very small during conduction, the gate drive voltage can turn on the MOSFET *Mp* properly. The inputs to the comparator *CP*2 are connected in such a way that the output is negative when the value of the duty cycle is higher than the sawtooth waveform. Therefore, both the MOSFETs are turned on at the same time.

C. *Startup Circuit.*

The controller and gate driver circuits require a dual dc supply for their operation, and the startup circuit is used to provide this as shown in Fig.5. The voltage nodes V_{A+} and V_{A-} denote the positive and negative dc voltages which power the controller and gate driver in the converter system. Batteries E1 and E2 provide the startup power to charge capacitors *Ca* and *Cb* through diodes *Dc* and *Dd*. With the controller and driver circuits operating, capacitors *Ca* and *Cb* start getting charged by the microgenerator through diodes *Da* and *Db*. This boost mechanism is similar to the

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charging of capacitors C2 and C3 in the split-capacitor topology. Furthermore, these capacitors are designed to maintain steady dc voltage while powering the auxiliary circuits. The nominal value of battery voltages are chosen to be less than steady-state voltages of capacitors *Ca* and *Cb*. Therefore, when the converter is operating, capacitors *Ca* and *Cb* are charged by the energy harvesting converter. Under this condition, diodes *Dc* and *Dd* become reverse biased and batteries E1 and E2 are cut off from the circuit.

It should be noted that the batteries utilized for startup are of really small capacity and footprint. Once the converter starts operating, capacitors *Ca* and *Cb* can be used to keep batteries E1 and E2 charged. If they get discharged, the dc bus voltages V_{A+} and V_{A-} on capacitors *Ca* and *Cb* charge these batteries through diodes D_{R1} and D_{R2}. These diodes are so chosen that they only get forward biased when the battery voltage drops below a nominal voltage of 3 V. The connecting resistors R_{R1} and R_{R2} are chosen to limit the charging current in the batteries.

IV. SIMULATION RESULTS

The proposed direct ac-dc converter was simulated in LTspice (Fig.7) and the results obtained are shown to verify the operation of the converter. The values of various parameters used are presented in Table I.

A sinusoidal ac voltage with an amplitude of 400mV anf frequency 100Hz is given instead of the microgenerator output for simulation of the proposed scheme. The LTspice model of the proposed converter is shown in Fig. 8. The converter is operated in Discontinuous Conduction Mode (DCM) to reduce switching losses.

The battery voltages for the auxiliary dc voltage supply are chosen as 3V. To obtain a regulated output voltage a single op-amp based proportional controller is used and the reference voltage given for the controller is 1.65V and the duty ratio obtained is .16. The bidirectional switch is realized by connecting an n-channel and p-channel MOSFETs in series.

TABLE I
CONVERTER CIRCUIT COMPONENTS

Parameter	**Value**
Switching Frequency	10kHz
Input Voltage	400mV, 100Hz
Output Voltage (Targeted)	3.3V
Load Resistance	1kΩ
Capacitor (C1)	22µF
Capacitor (C2 and C3)	4.7µF
Inductor (L)	10µH
Filter capacitor	420µF
Resistors used for controller	100Ω

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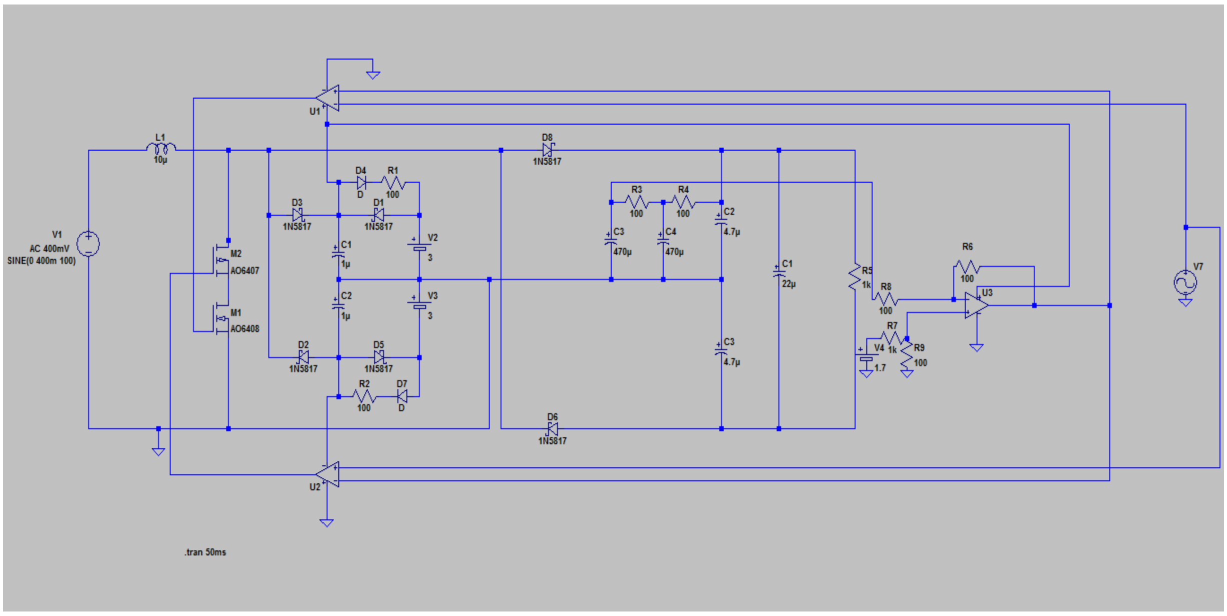

Fig. 7 LTspice model of proposed converter with auxiliary circuits.

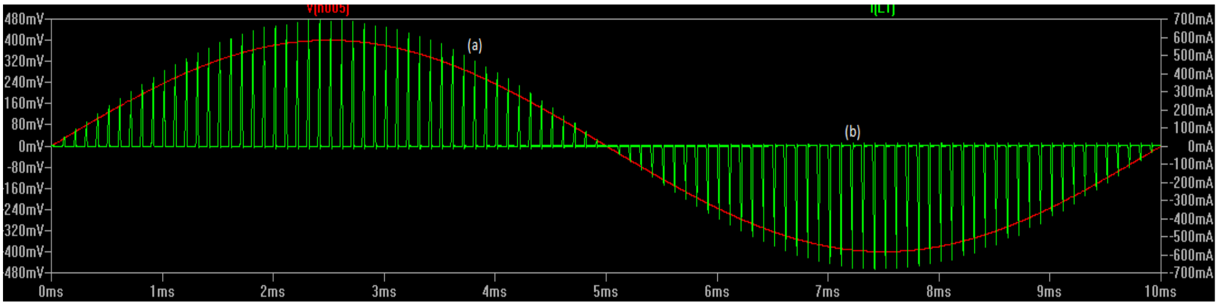

Fig. 8 (a) Input voltage (b) Input current

The converter is operated at a switching frequency of 10kHz with a nominal load of 1 kΩ. The input voltage and input current for converter are shown in Fig. 8. In practical case due to nonlinear operation of microgenerator the input voltage is not an ideal sinusoid. But here the simulation is done with a pure sinusoid waveform. It can be seen that the converter operates in DCM and the input current follows the input voltage profile. The input current over a few switching cycles is shown in Fig. 11 along with positive gate signals.

The converter is operated in DCM to reduce switching losses. The gate pulses for MOSFETs *Mn* and *Mp* generated by comparators *Cp*1 and *Cp*2 are shown in Fig. 10. It can be seen that the gate voltage of the n-MOSFET (*V*gn) is positive when the p-MOSFET gate voltage (*V*gp) is negative. Therefore, both the MOSFETs are turned ON at the same instant.

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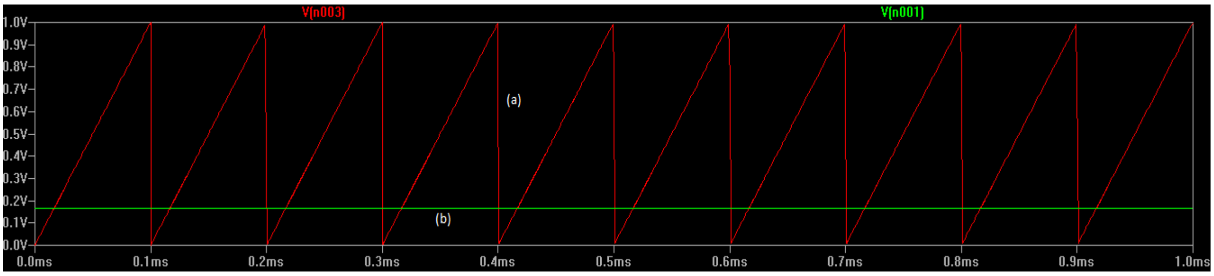

Fig.9 (a) Sawtooth waveform (b) Duty cycle.

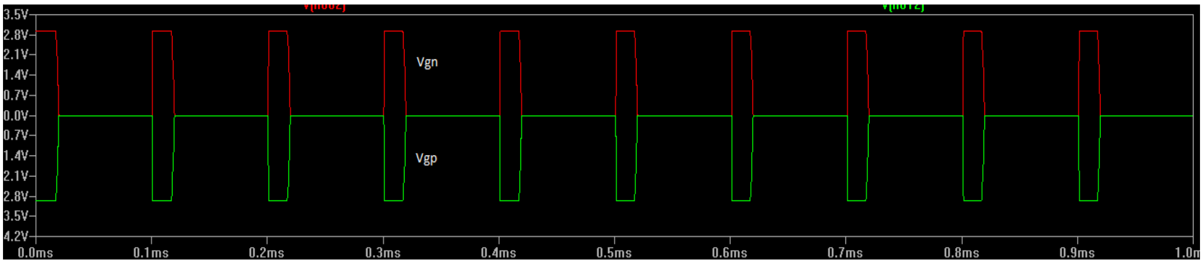

Fig. 10 PWM waveforms for MOSFETs Mn and Mp.

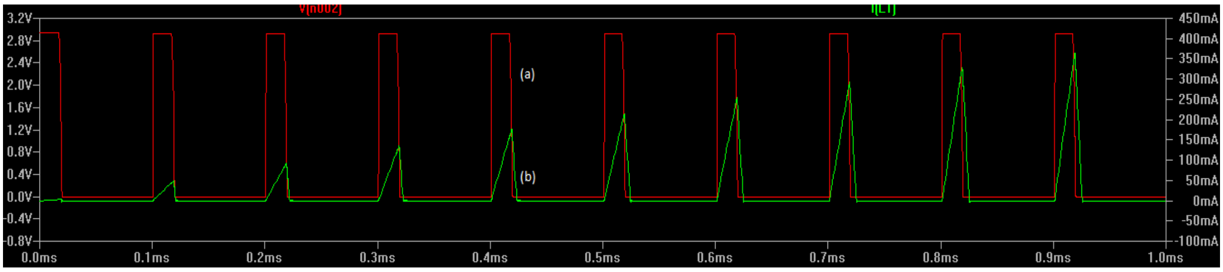

Fig. 11 (a) Input current (b) Gate pulses.

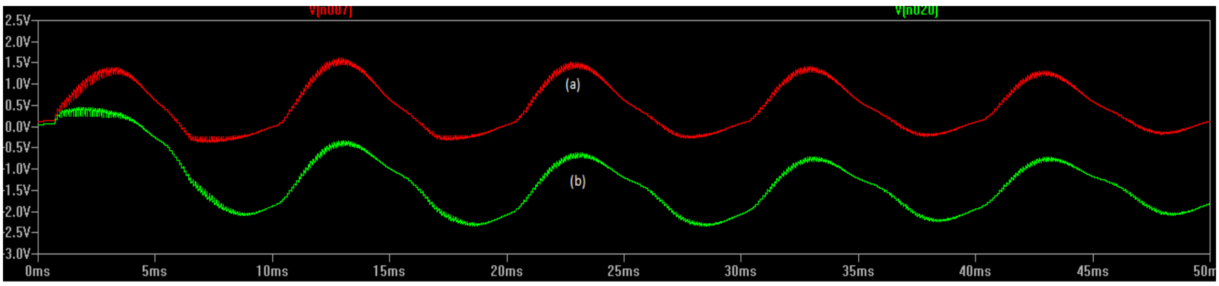

Fig. 12 Voltage across capacitors (a) C2 and (b) C3

The voltage across capacitors C2 and C3 are shown in Fig. 12 . From figure it is clear that the two capacitors C2 and C3 charge and discharge in alternate half cycles. Capacitors C2 and C3 have positive and negative voltages with respect to the system ground, which is the basis for the dual dc supply design for the controller and driver circuits.The dc bus voltages V_{A+} and V_{A-} are shown in Fig.13. The bus is initially powered by the batteries and has a steady voltage without any ripple. As the output voltage builds up, the batteries are cutoff from the circuit and capacitors *Ca* and *Cb* are charged by the energy-harvesting converter. It can be seen that the capacitors are now charged in alternate half cycles while continuously powering the gate driver and controller circuits.

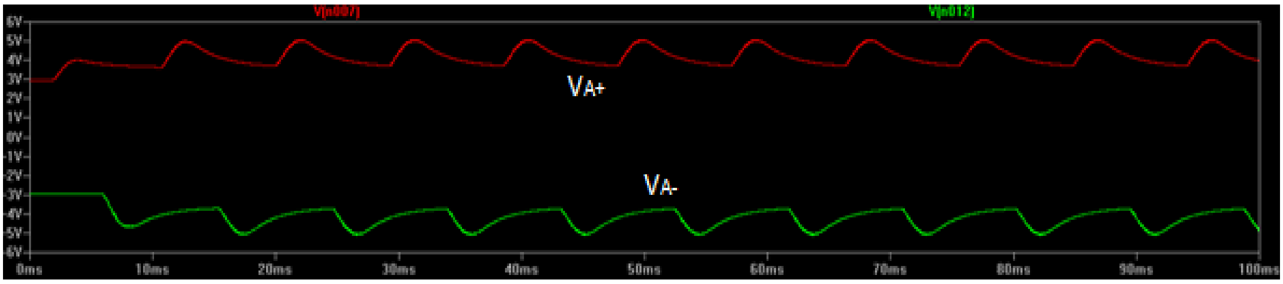

Fig. 13 DC bus voltages VA+ and VA-

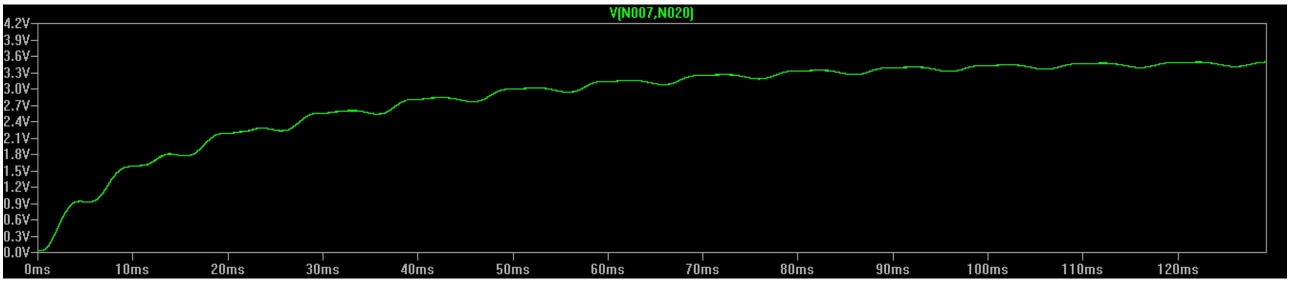

Fig. 14 Output voltage

The output voltage waveform for a duty cycle of .16 is shown in Fig. 14. It can be seen that the output voltage reaches a steady state value of 3.3 V within 50 milliseconds. The proportional controller is used to regulate the output voltage. A single op-amp based proportional controller is used for this.

IV. CONCLUSION

This paper has presented a direct ac-dc boost converter for microgenerator based energy harvesting applications. The use of the bidirectional switch helps to boost the low ac microgenerator voltage to a dc voltage in both the input half cycles. The bidirectional switch is realized by connecting a n- and p- MOSFETs in series. A gate driver circuit and a control circuit is proposed inorder to obtain a constant output voltage. A startup circuit and auxiliary dc supply circuit is used to provide required dc supply for the operation of gate driver and control circuits. The auxiliary circuits are designed in such a way that they consume low power for their operation. The circuit is suitable for self powered wireless devices such as sensor nodes, medical implants etc..

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