KIET IJCE KIET International Journal of Communications & Electronics
Volume. No. 5, Issue No. 2, July-December 2017, ISSN: 2320 - 8996

A 99% Efficient, 3 volts Solar Energy Harvesting System for Wireless Sensor Network Nodes

Himanshu Sharma[1],Ahteshamul Haque[2], Kasak Agarwal[3], Kajal Mishra[4]
[1,3,4]KIET Group of Institutions, Ghaziabad, U.P. India
[2]Jamia MilliaIslamia, New Delhi

Abstract- This paper focuses on design and analysis of DC-DC converters for low-power Photovoltaic (PV) energy harvesting applications such as Wireless Sensor Network (WSN) Nodes. The WSN nodes consume power due to their use in continuous monitoring and control applications. Therefore, to provide prolong network life time to WSN nodes photovoltaic energy harvesting may be used for battery charging. In this paper,buck, boost, buck-boost, Cuk and SEPIC converters are simulated in PSIM software and different currents and voltages waveforms have been analyzed. Secondly, their mathematical modeling equations have been simulated in MATLAB and graph has been plotted. From different graphs, the performance parameters have been evaluated for wireless sensor network nodes requirements. Our simulation results prove that the power efficiency of the boost converter reaches 85% and most suitable for WSNs.

***Keywords-* DC-DC Converters, Performance Analysis, Photovoltaic energy harvesting, Wireless Sensor Network Nodes**

I. INTRODUCTION

The conventional Wireless Sensor Networks (WSNs) has the design problem of high power consumption (in mWrange)during their continuous operation in monitoring and control applications. This design problem has been tackled by mainly duty cycle based approach till now. In this paper, we present an innovative idea of the solar energy harvesting which is a new design solution to the energy constrained WSN nodes. The solar photovoltaic (PV) energy harvesting refers to converting solar light energy into electrical energy to operate an electrical or electronic device. As applied to WSNs, the solar energy is converted into electrical energy and is utilised to operate a WSN node. The electrical energy harvested from solar energy (sunlight) can be used directly to power WSN node. Alternatively, the harvested energy can be stored in a rechargeable battery (or supercapacitors) for the future purpose (e.g. during night time when sunlight is not available).The solar energy harvesting wireless sensor networks (EHWSNs) consist of small autonomous wireless sensor nodes attached to small size solar panels for their energy harvesting needs. The EHWSN are used for monitoring and control applications of the environmentvariables such as light, temperature, Humidity, pressure and acceleration monitoring of any area/plant/process.

1.1 DC to DC converters: The DC-DC converter is a power electronic device, which is used to convert the voltage amplitude from one level to another level [1]. The

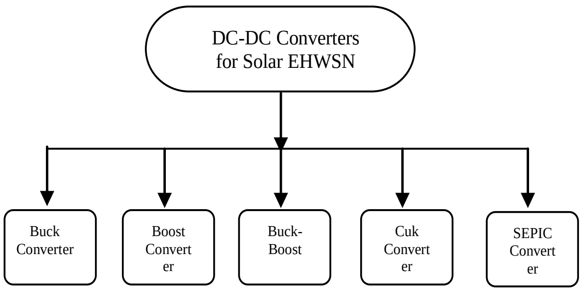


Fig.1 DC-DC converters for solar EHWSNs

voltage levels range from very low (mV) to high (volts) values. The main types of dc to dc converters topology are shown in fig.1 as:

- Boost Converter,
- Buck Converter,
- Buck-Boost converter
- Cuk Converter
- Single End Primary Inductor Current (SEPIC)

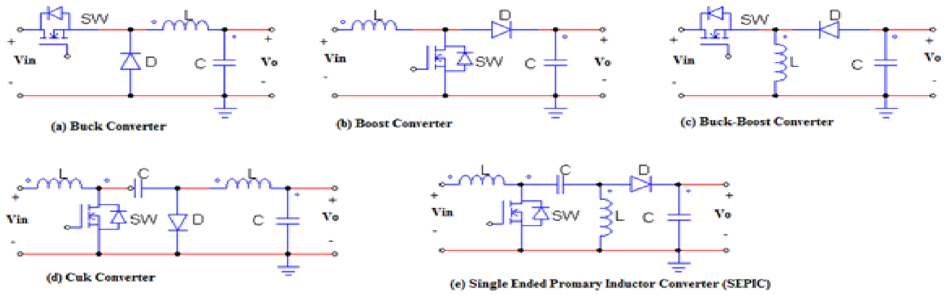
The boost converter increases the amplitude of harvested energy by using capacitors and inductor and a switch (MOSFET). The buck converter is used to decrease the amplitude of harvested energy if the excess amount of energy is received by the solar panel. The Buck-BoostConverter performs both actions of increase/decrease using the single common circuit. Generally, in photovoltaic applications, the boost converter is mostly used because the received power from the sun is very low (~mW). Some common topologies of DC-DC converters are shown in

Fig.1. The switches are practically implemented by using MOSFETs.

II. II. LITERATURE SURVEY ON DC-DC CONVERTERS

The major research issue in DC-DC converters is switching frequency, switching losses, resistive losses, Inductor selection, and capacitor selection. Chowdary G. and Chatterjee S. [2] have proposed a 300-nW sensitive, 50-nA DC-DC converter integrated circuit (IC) for solar energy harvesting applications. The circuit can harvest energy whenever the available power is greater than 0.3µW. The Efficiency (η) at 0.3 µW is 25%, at 0.5 µW is 37%, at 1 µW is 48% and at greater than 2 µW is 50%. Chowdary G. et al. [3] have presented an 18 nA, 87% efficient solar, vibration and RF Energy-harvesting power management system with a single shared inductor.

In this paper, they have proposed a modular MPPT based DC to DC buck-boost converter that can harvest from multiplesources over a range of available powers (from nW to μW) with one shared inductor.



(a) Buck Converter (b) Boost Converter (c) Buck-Boost Converter (d) Cuk Converter (e) Single Ended Promary Inductor Converter (SEPIC)

Sr. No.	DC-DC converter Topology	Author	Year	Main points/ Equation	Numerical Results / DC-DC Converter Efficiency (η%)= (P_{out} / P_{in}) x100	Limitations	Our Comments
1	Boost Converter with MPPT	Chowdary G. and Chatterjee S. [2]	2015	Process : 0.18 µm, Output Voltage :1-2volts, Current consumption : 50nA, Startup Mechanism: External $P_{in(min.)}$: 0.3µW, Chip Area :1 mm x 0.2 mm	At 0.3µW η=26 %, At 2 µW η=52 %, At 10 µW η=76%	A bulky external Startup Inductor is used.	The startup circuit can be fabricated inside the chip also using Switched Capacitors (SC).
2	Boost converter with Open Circuit Voltage(OCV) type of MPPT.	Chowdary G. et al. [3]	2016	An oscillator is used instead of comparator, No current sensing used.	η = 87% at 20 μW input power	Current sensing is not used.	MPPT is obtained at small power levels
3	To remove large size inductor the switching capacitors (SC) are be used.	YifengQiu et al. [4]	2011	Process: 0.18µm CMOS. Startup Mechanism: Not reported, The DC-DC converter can boost 0.35V input to to 5.2V	Single voltage doubler η = 70%, end to end efficiency η = (P_{out} / P_{mp}) x100is 35%.	Operation is limited to the µW ranges.	Improved efficiency
4	A DC-DC converter with switched capacitor is presented	Wanyeong Jung et al. [5]	2014	Process: 0.18µm CMOS. Startup Mechanism: Cold start,	voltage doubler η = 75%,	Cold start system	A Switch capacitor based DC-DC voltage doubler circuit, is used as boost converter
5	A minimum power consumption output voltage detector (OVD) is proposed	Qing Liu et al. [6]	2012	Process: 0.18µm CMOS, Startup Mechanism: Charge Pump based self-startup, Min Input Voltage: 30mV Output Voltage: 1.8V MPPT:Yes synchronous boost converter	Efficiencyη:84% @180µW	High Power Efficiency	idle power consumption is very small i.e. 1.9µW.
6	A regulated charge pump with MPPT algorithm	Jungmoon Kim et al. [7]	2011	Process: 0.35µm CMOS, Startup Mechanism: Charge Pump , Controller Power:850nW Min Input Voltage: 30mV Output Voltage: 2 V MPPT:Yes	End to End Efficiency η = 86 % @ 35 µW	Input voltage range is 1-2.7 volts	No current sensor required that consumes more power

YifengQiu et al. [4] have proposed a 5µW-to-10mW input power range inductive boost converter for indoor photovoltaic energy harvesting with integrated maximum power point tracking algorithm. Wanyeong Jung et al. [5] have proposed a 3nW fully integrated energy harvester based on Self-oscillating switched-capacitor, dc-dc converter for wireless sensor networks. Qing Liu et al. [6] have proposed an integrated circuit (IC) for a DC-DC boost converter for energy harvesting applications with 30-300mv input, ultra-low power and self-startup features. Jungmoon Kim et al. [7] have presented a regulated charge pump with a low-power integrated optimum power point tracking algorithm for indoor solar energy harvesting application.

III. DC-DC converter Performance Parameters:

Table 2 shows the mathematical equations of DC-DC converter performance parameters as [28]:

- Duty Cycle (D)
- Operating Frequency (f)
- Inductor ripple current (ΔI_L)
- Capacitor ripple voltage (ΔV_c)
- DC-DC conversion efficiency (η)
- Diode Conduction losses
- MOSFET Switching Losses
- Losses in storage devices (inductor and capacitor)
- Switching Stress on MOSFET
- Total power loss

Duty Cycle (D) Control of DC-DC Converters:
The DC-DC converter operation can be controlled by controlling the duty cycles of MOSFET switch. In constant duty cycle operation mode, the switching frequency is kept constant and only ON time (t_1) is varied. In variable duty Cycle Operation, either ON time (t_1) or OFF time (t_2) is kept constant and switching frequency is varied.

Operating Frequency (f):
At higher switching frequency the switching losses in the MOSFET increases. Thus overall efficiency (η) is decreased. At lower switching frequency, the value and size of capacitor and inductor is increased. Thus a tradeoff between size and efficiency is to be maintained.

Inductor Selection:
The critical value of inductor determines continuous or discontinuous mode of operation of DC-DC converter for a given duty cycle (D), frequency (f) and load resistor R_L. The critical value is the minimum value of the inductor (mH) below which the converter goes into discontinuous conduction mode.The critical values of inductor L_c is given as:

For Buck Converter:

$$L_c = L = \frac{(1-D)R}{2f} \quad ...(1)$$

For Boost Converter:

$$L_c = L = \frac{D(1-D)R}{2f} \quad ...(2)$$

For Buck-Boost Converter:

$$L_c = L = \frac{(1-D)R}{2f} \quad ...(3)$$

For Cuk Converter:

$$L_{c1} = L_1 = \frac{(1-D)^2 R}{2Df} \quad ...(4)$$

$$L_{c2} = L_2 = \frac{(1-D)R}{2f} \quad ...(5)$$

Capacitor Selection:
The capacitor acts as a filter to the output voltage V_0. It has equivalent series resistance (ESR). The ESR value should be low to increase the efficiency.

For Buck Converter:

$$C_c = C = \frac{(1-D)}{16Lf^2} \quad ...(6)$$

For Boost Converter:

$$C_c = C = \frac{D}{2fR} \quad ...(7)$$

For Buck-Boost Converter:

$$C_c = C = \frac{D}{2fR} \quad ...(8)$$

For Cuk Converter:

$$C_{c1} = C_1 = \frac{D}{2fR} \quad ...(9)$$

$$C_{c2} = C_2 = \frac{D}{8fR}$$

...(10)

Table 2: Performance parameters of DC-DC Converters

Sr. No.	Performance Parameters	(a) Buck Converter	(b) Boost Converter	(c) Buck-Boost Converter	(d) Cuk Converter	(e) SEPIC Converter
1	Output Voltage (V_o)	$Vo = Vin.D$	$V_o = \frac{V_{in}}{(1-D)}$	$V_o = -\left(\frac{D}{1-D}\right)V_{in}$	$V_o = \left(\frac{D}{1-D}\right)V_{in}$	$V_o = \left(\frac{D}{1-D}\right)V_{in}$
2	Duty Cycle (D)	$D = \frac{V_o}{V_{in}}$	$D = 1 - \frac{V_{in}}{V_o}$	$D = \frac{V_{in}}{V_o}$	$D = \frac{V_o}{V_o - V_{in}}$	$D = \frac{V_o}{V_o + V_{in}}$
3	Inductor Ripple Current (ΔI_L)	$\Delta i_L = \frac{V_{in}\ D}{f.L}$	$\Delta i_L = \frac{V_{in}\ D}{f.L}$	$\Delta i_L = \frac{V_{in}\ D}{f.L}$	$\Delta i_{L1} = \frac{V_{in}\ D}{f.L_1}$ $\Delta i_{L2} = \frac{V_o\ D}{f.L_2}$	$\Delta i_{L1} = \frac{V_{in}\ D}{f\,L_1}$ $\Delta i_{L2} = \frac{V_o}{L_2}\left(\frac{D(1-D)}{D-1}\right)$
4	Capacitor Ripple Voltage (ΔV_c)	$\Delta V_c = \frac{i_o\ D}{f.C}$	$\Delta V_c = \frac{i_o\ D}{f.C}$	$\Delta V_c = \frac{i_o\ D}{f.C}$	$\Delta V_{c1} = \frac{i_{in}(1-D)}{f.C_1}$ $\Delta V_{c2} = \frac{V_{in}\ D}{f^2 C_2 L_2 D}$	$\Delta V_{c1} = \frac{i_{in}(1-D)}{f.C_1}$ $\Delta V_{c2} = \frac{(1-D)(i_{in}L_2 - V_{in}D)}{f.C_2L_2}$
5	Converter Efficiency(η)	P_0 / P_{in}	$P_0 / P_0 + P_{loss}$	P_0 / P_{in}	P_0 / P_{in}	P_0 / P_{in}
6	Diode Conduction losses	Medium	Medium	Less	High	High
7	MOSFET Switching losses	Less	High	High	Medium	Less
8	Losses in Energy Storage elements (L&C)	Low at Lower Input Power Levels(Pi)	Medium	Medium	High	High
9	Switching stress on Semiconductor Elements	Low	Medium	Medium	High	High
10	Total Power Loss in DC-DC Converter	High	Low	Medium	Low	Low

IV. BUCK CONVERTER

In Buck converter, the average output voltage (Va) is less than the input voltage (Vin).

Operation: When MOSFET switch is closed at time t_1, the input voltage V_{in}appears across the load resistor R_L. if the MOSFET switch remains OFF for the time t_2 , then the voltage across the load resistor R_L is zero. The amplitude of output voltage V_0 is less than the input voltage V_{in}.

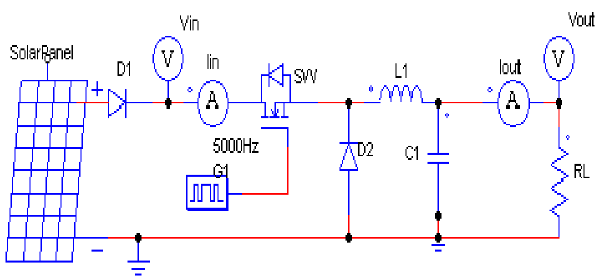


Fig.3 Buck Converter

Output Voltage: The average output voltage of buck converter is given by

$$V_0 = \frac{1}{T}\int_0^{t_1} v_o\,dt = \frac{t_1}{T}V_{in} = f.t_1.V_{in} = V_{in}.D \quad ...(11)$$

The average load current at output is given by

$$I_0 = I_L = V_0 / R = D.V_{in} / R \quad ...(12)$$

Where, T = chopping period, D = t_1 / T is duty cycle, f = chopping frequency.

Table 3: Buck Converter Simulation Parameters:

Simulation Parameters	Value
Input Voltage ,Vin	1.5v dc
Output Voltage, Vo	0.8v dc

Capacitor, C_1	500uF, 5v
Inductor, L_1	500uH , 5v
MOSFET Switching Frequency(f)	50Hz
Load Resistor,R_L	20 ohm

Table4:Solar Panel Parameters:

Simulation Parameters	Value
No. of Cells in Series(N_s)	2 (0.8v each)
Max. Power ($P_{max.}$)	0.5 watts
Silicon material Energy Band Gap (Eg)	1.12 eV
Solar Panel (2 solar cells in series connection)	Voc=1.6 V, Isc=2 A, Vm=1.5 V, Im=1.8 A
Light Intensity	1000 watts/m^2 or 100 milli watts/cm^2
Temperature	25 Degree Celsius

Buck Converter Simulation Results:

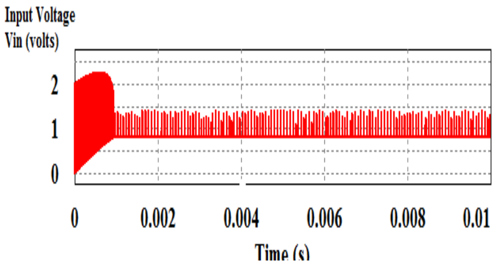


Fig. 4 Buck Converter Input Voltage from Solar Panel

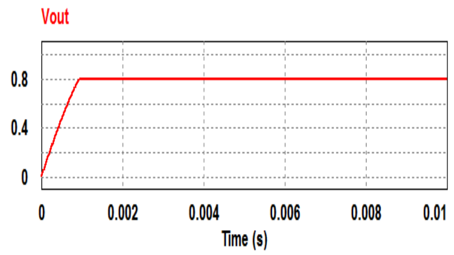


Fig.5 Buck Converter Output Voltage to the load

V. BOOST CONVERTER

A boost converter increases the DC input voltage and gives at the output.A boost converter circuit is shown in fig.2. It consists of an Inductor, a MOSFET switch, a PWM signal generator, a diode, a capacitor and a resistive load.

Operation: When switch is closed, the current rises through the inductor (L) and the MOSFET switch.

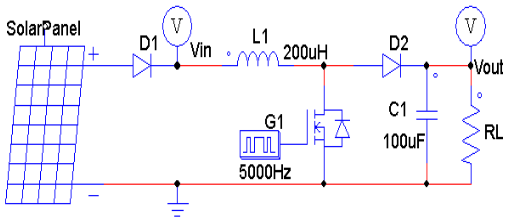


Fig.6 A 99% efficient 3 volts solar energy harvesting boost converter for WSN nodes

Table 5: Boost Converter Simulation parameters

Simulation Parameters	Value
Input Voltage ,Vin	1.5v dc(rippled)
Output Voltage, Vo	3.3v dc
Capacitor, C_1	100uF, 5v
Inductor, L_1	200uH , 5v
MOSFET Switching Frequency(f)	5KHz
Load Resistor,R_L	10 ohm

Boost Converter Simulation Results:

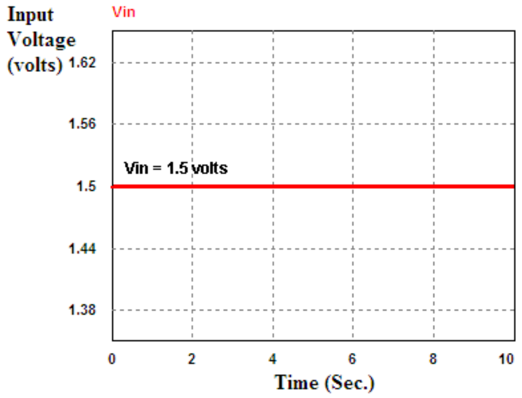


Fig.7 Input Voltage to the Boost Converter from Solar Panel

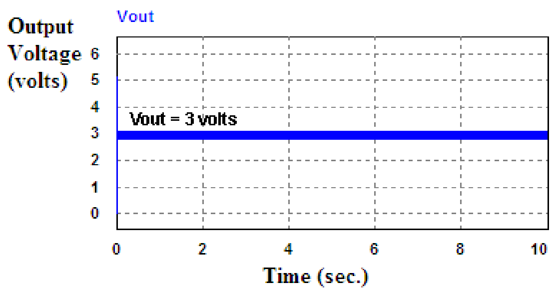


Fig.8 Output Voltage of Boost Converter to the load

VI. EFFICIENCY CALCULATIONS

The boost converter efficiency is defined as output power (P_0) divided by sum of output power (P_0) and losses. Here; Output power is calculated by the formula as

$$P_0 = \frac{D.(V_{in} - V_{sw})^2}{R} \quad \dots (13)$$

Where, V_{sw} is Switching loss of converter, D is duty cycle, R is load resistance and V_{in} is input dc supply voltage from solar panel. In this experiment D=0.5, V_{in} = 1.5 volts dc, V_{sw} = 0.2 volts, and R = 10 ohms. So using equation 13 the input power calculated is approximately 65mW. Now the efficiency is calculated as

$$Efficiency\ (n) = \frac{P_0}{P_0 + P_{loss}} \quad \dots (14)$$

Let, the power loss due to switching loss is 0.5mW. Then, boost converter efficiency (η) is 65mW/65.5mW= 99.23%.

7. Conclusion:

In this paper, the performance parameters of DC-DC converter have been analyzed. A boost converter simulation have also been performed in PSIM simulator. The input and output voltages have been plotted and shown for performance analysis. From the simulation it is observed that in DC-DC converters the desired output voltage can be obtained by proper selection of component values of Inductor, capacitor and switching frequency. The efficiency (η) of out desined boost converter is 99.23% which is very useful for solar energy harvesting wireless sensor network nodes.

VII. REFERENCES

[1] S.Sivakumaretal. "An assessment onperformance of DC–DC converters for renewableenergy applications" RenewableandSustainableEnergyReviews, Elsevier, vol. 58, 2016, pp. 1475–1485.

[2] A 300-nWSensitive, 50-nA DC-DC Converter for Energy Harvesting Applications, GajendranathChowdary and Shouri Chatterjee, IEEE Transactions on circuits and systems, Volume: 62, Issue: 11, Nov. 2015, pp. 2674 – 2684.

[3] An 18 nA, 87% efficient solar, vibration and RF energy-harvesting power management system with a single shared inductor, GajendranathChowdary, Arun Singh, and Shouri Chatterjee,IEEE Journal of solid-state circuits, vol. 51, no. 10, october 2016, pp.2501-2513.

[4] 5µW-to-10mW Input Power Range Inductive Boost Converter for Indoor Photovoltaic Energy Harvesting with Integrated Maximum Power Point Tracking Algorithm,YifengQiu, Chris Van Liempd, Bert Op het Veld, Peter G Blanken,Chris Van Hoof, IEEE International Solid-State Circuits Conference, ISSCC 2011, pp.118-120.

[5] A 3nW Fully Integrated Energy Harvester Based on Self-Oscillating Switched-Capacitor DC-DC Converter, Wanyeong Jung, Sechang Oh, Suyoung Bang, Yoonmyung Lee, Dennis Sylvester, David Blaauw, IEEE International solid-state circuits conference, ISSCC 2014.

[6] 30-300mV Input, Ultra-low Power, Self-startup DC-DC Boost Converter for Energy Harvesting System, Qing Liu, Xiaobo Wu, Menglian Zhao, Lu Wang, Xiaoting Shen, IEEE AsiaPacificConference on Circuits and Systems (APCCAS), 2012, pp.432-435.

[7] J. Kim, J. Kim, and C. Kim, "A regulated charge pump with a low power integrated optimum power point tracking algorithm for indoor solar energy harvesting," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 58, no. 12, pp. 802–806, Dec. 2011.

[8] M.H. Rashid, "Power Electronics circuits, devices and applications", 3rd Edition Prentice Hall of India (PHI),2012.

[9] NPTEL Power Electronics Module 1 "Power Semiconductor Devices", IIT Kharagpur lecture notes, 2015.