Indian Journal of Geo Marine Sciences
Vol.46 (11), November 2017, pp. 2241-2249

Design and performance analysis of boost converters in an energy harvesting system for underwater applications using sea water in microbial fuel cell

P. Janani[1] & S. Sakthivel Murugan[2]

[1] Infosys, Chennai, [2] ECE Department, SSN College of Engineering, Chennai, 603110, India
[E.Mail: jananiprabakaran17@gmail.com, sakthivels@ssn.edu.in]

Received 05 August 2015; revised 02 November 2016

Present study consists of an innovative energy harvesting system for low power devices. This harvesting system uses ocean water/ river water, sea sand, bacteria's in ocean water using Microbial Fuel Cell as a source for power generation. The energy harvesting system consists of Microbial Fuel Cell and a power management system. Performance analysis of MFC is carried using Stainless Steel as anode and Magnesium as a cathode with waste milk , waste vegetables, soil, red sand, sea water collected at shallow water, sea sand, etc. are the various source samples. MFC is able to achieve more than 1V. Power management system consists of Charge Pump, Super capacitor and Interleaved Boost Converter (IBC). The developed energy harvesting system results in generating 6.8 V which is the requirement of the load. Thus the designed energy harvesting system provides relentless and justifiable power supply for remote underwater sensing, surveillance devices including data collections. Simulation results of energy harvesting system are carried out using Linear Technology (LT) spice.

[Keywords- Microbial Fuel Cell, Interleaved Boost Converter, Charge Pump, Super capacitor, energy efficiency].

Introduction

Fuel cell is one of the propitious energy technologies used for the tenable future with its high energy efficiency and environment friendly nature. In comparison with other types of fuel cells, MFC also called as biological fuel cell can use any organic material to feed the fuel cell and the developed energy is used as a source for harvesting electricity in ocean water. The use of MFC's is very attractive for low power applications and also it is a clean and efficient method for energy production[1, 2].

MFC is a device that converts chemical energy to electrical energy by using active bacteria and simulates the interactions between the bacteria found in nature [3, 4 ,5].MFC generates an output voltage less than 0.7V with low output current in the range of few mA. To address this issue, a power management system is required between the MFC and the load. Thus the harvested energy from the MFC is transferred to the load with the boosted voltage of MFC to meet the load requirement. The underwater energy harvesting system using marine sediment MFC has two major interface circuits. They are Converter Transformer Capacitor (CTC) and Charge Pump Capacitor Converter (CPC). The CTC requires two supercapacitor and an additional circuitry to control circuits which decreases energy conversion efficiency due to large overhead while CPC requires one supercapacitor and achieves better energy conversion efficiency.

In this paper, the underwater energy harvesting system consists of marine sediment MFC and its associated power management system. The power management system consists of charge pump, supercapacitor and boost converter. The power management system is designed to accommodate the unique features of MFC and also achieves better energy conversion efficiency. Simulation results in a 1um CMOS process clearly shows the existence gives the advantage of power management system for powering oceanographic instruments.

The rest of the paper is organized as follows. In section 2, we present the design of the marine sediment MFC. In section 3, we develop a power management system which consists of a charge pump, supercapacitor, boost converter and interleaved boost converter along with their design considerations for the MFC. In section 4, we evaluate the energy harvesting system.

Materials and Methods

Development of MFC

Modeling of fuel cell is important for the prediction of accurate output characteristics. While modeling the fuel cell mathematically and electrically, the voltage drop due to over-potential or polarization is also taken into considerations. The output of the single fuel cell is 0.7V. In case of stacking many cells in series then the corresponding output will be of higher voltage. The stacked output of fuel cell can be increased to the required level with the help of a power management system like charge pump, supercapacitor and boost converter which converter a lower DC voltage to a higher DC voltage.

MFC Modeling

Microbial Fuel Cell can be treated as a weak voltage source because the output voltage does not remain constant as the current output increases. The basic equivalent circuit of MFC is shown in Fig. 1.

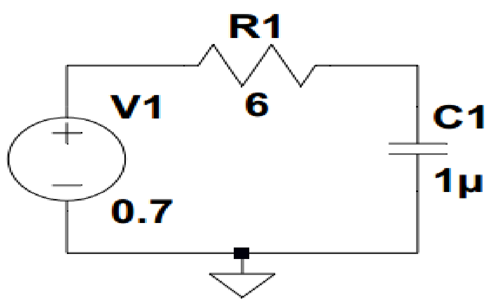

Fig. 1- Equivalent circuit of MFC

This can be electrically modeled as voltage source and resistance. The MFC internal resistance is the sum of system ohmic resistance, charge transfer resistance and activation resistance. The internal voltage and resistance can vary non-linearly as MFC condition changes. The potential difference between the anode and cathode when the circuit is in open is called Open Circuit Voltage (OCV). The Open Circuit Voltage (OCV) of Microbial Fuel Cell is generally less than 0.7V. The typical method of characterizing MFC power production is operating the Microbial Fuel Cell with a series of external resistance between the anode and cathode, and monitoring voltage across the resistor continuously to obtain the polarization data.

The equivalent circuit of a MFC consists of a DC Voltage Source and Internal Resistance. One end of the voltage source is connected to the resistor and then to a cathode terminal. Other end of the voltage source is connected to the anode terminal. Thus, output voltage is measured at the cathode and anode terminal of that circuit.

The output power of a MFC reactor varies according to the load current at a relatively long settling time. The output power across external resistance which is inversely proportional to the total system resistance can be measured as follows:

$$P_0 = \frac{{V_{int}}^2 R_{ext}}{(R_{int} + R_{ext})^2} \quad (1)$$

Where V_{int} is the internal voltage, R_{int} is the internal resistance and R_{ext} is the external resistance of Microbial Fuel Cell (MFC).

The output power is also in proportion to the square of the internal voltage. When internal resistance and external resistance are same, the internal resistance at the maximum power point can be estimated. The internal voltage at maximum power point can also be estimated using internal resistance and measured current is pointed[6].The power measurement on static external resistance on MFC output can simulate the MFC output power to load.

Microbial Fuel Cell produces an output voltage in the range less than 0.7V and the current output in the range of few mA, which cannot be used directly in the real-world applications. So, a power management system is developed. The power management system consists of Charge Pump, Supercapacitor and Boost Converter. The details about the power management system along with their design considerations will be discussed in the next section.

Design of the power management system

To address the above mentioned problem, a power management system is required to convert a low voltage to high voltage. The power management system consists of charge pump, supercapacitor and boost converter. A power management circuit allows efficient transfer of energy from a temporary storage element known as the supercapacitor to load. The devised Energy Harvesting System (EHS) is illustrated in Fig. 2.

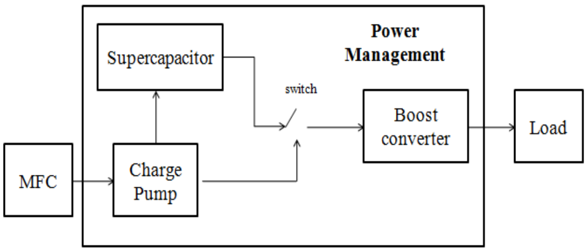

Fig. 2 - Energy Harvesting System

Microbial Fuel Cell produces an output voltage of less than 0.7V. Since the voltage produced by the Microbial Fuel Cell is of less voltage it is connected to the load through a power management circuit. The power management circuit comprises of charge pump, supercapacitor and boost converter.

The output of the microbial cell is 0.7V; it is it is connected to a charge pump. The charge pump produces an output voltage twice that of the input voltage (i.e.) $V_{out} = 2 * V_{dd}$, which is then being connected to the supercapacitor. Once the supercapacitor is charged to 1.4V, charge pump establishes the connection between the supercapacitor and boost converter and the boost converter boosts that voltage to 6.8V. The output voltage of the boost converter is then connected to the load.

Charge pump circuits are widely used in integrated circuits due to the continuously power supply reduction. Charge pump is a kind of DC-DC converter that uses capacitors as energy storage elements to create either a higher or lower voltage power source. A Charge Pump is an electronic circuit that converts the supply voltage V_{DD} to a DC output voltage V_{out} which is several times higher than the supply voltage V_{DD}. Unlike other traditional DC-DC converters, which employ inductors, CP's are only made of capacitors and switches [7]. Charge pump consists of a pumping capacitance, two switches and the load which is represented by a capacitor and current generator. Here the operation of Charge Pump Circuit is explained in the Fig. 3.

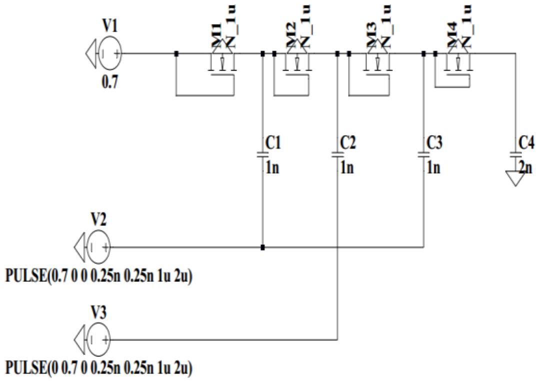

Fig. 3 Charge Pump

During first half period, switch S1 is closed and switch S2 is open and the capacitance being connected to the power supply is charged to V_{DD}, while the output node is discharged by the current load. During second half period, switch S1 is open and switch S2 is closed, the clock signal now equals to V_{DD}, thus part of the charge stored in C is transferred both to capacitive load and current load. Hence, at each cycle the output voltage will increase up to the asymptotic value which is equal to

$$V_{out} = 2V_{dd} - \frac{I_L T}{C} \quad (2)$$

Supercapacitor is also known as EDLC's (Electric Double Layer Capacitors). Supercapacitor has very high capacitance. The capacitance of a supercapacitor is two or three orders. The capacitance density or energy density is the important property. Energy density refers to the amount of charges that can be stored per unit Supercapacitor uses two layers of the dielectric material separated by a very thin insulator surface as the dielectric medium. The cost of supercapacitor is high.

SC behaviour can be represented differently in both steady state and dynamic state. They are grouped in three major categories:

- Time-domain identification leading to interleaved RC equivalent circuit model
- Frequency-domain identification by impedance spectroscopy model
- Electrochemical thermal principle identification.

All the three categories face some common drawback that they do not focus on some elementary phenomena during SC normal operation such as redistribution of residual charge during charging and relaxation phase. The main goal of SC model is to accurately predict the SC behaviour for long time dynamics. In the Fig.4, the basic operation of SC model is shown.

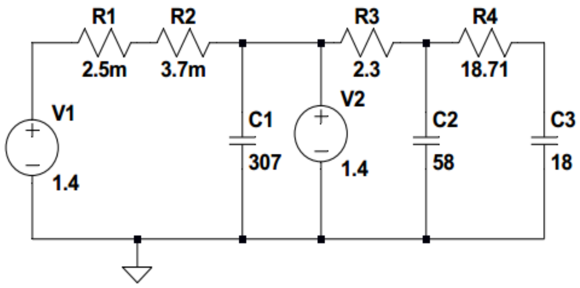

Fig. 4- Supercapacitor Model

Where R1 is the SC input electrode resistance, RL and CV are the resistance and the nonlinear capacitance of the so called SC network system model, R2 and C2 are the resistance and the nonlinear capacitance of the SC second branch, and R3 and C3 are the resistance and the nonlinear capacitance of the third SC branch, also two current sources I_{CH} and I_{RED} are included. These two devices allow for improving the SC dynamics by taking into account the diffusion of the residual charge during charge or discharge phases and redistribution one, respectively. The current generators I_{CH} and I_{RED} account for the diffusion of the Q_R and they are inherently inactive when the SC is charged for the first time.

For designing high efficiency fuel cell power systems, a suitable DC-DC converter is required. A normal boost converter converts a DC voltage to a higher DC voltage. Among the other topologies, Interleaved Boost Converter is considered as a better solution for fuel cell systems due to improved electrical performance. Interleaved Boost Converter gives better performance characteristics and reduces the ripple content also which includes increased efficiency, faster transient response, reduction in size and greater reliability.

Interleaved Boost Converter consists of a number of boost converters connected in parallel and controlled by the interleaved method which has the same switching frequency and phase. Here the operation of Interleaved Boost Converter is explained which is shown in the Fig. 5.

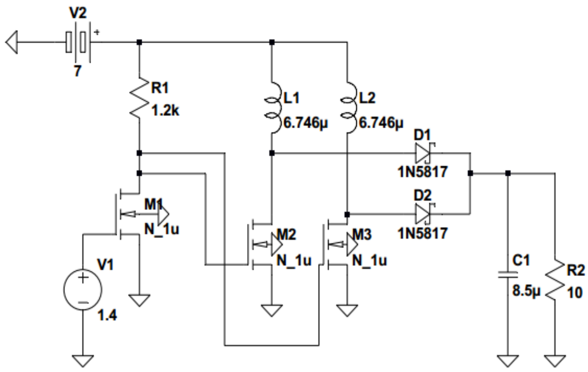

Fig. 5- Interleaved Boost Converter

When the device S1 is turned ON, the current in the inductor iL1 increases linearly. During this period, the energy is stored in the inductor L1. When the device S1 is turned OFF, diode D1 starts conducting and the stored energy in the inductor L1 ramps down with a slope based on the difference between the input and output voltage. The inductor starts discharging the stored energy to the load through the diode D1. After an half switching cycle of S1, S2 is also turned ON repeating same as S1 and completes the same cycle of events.

Interleaved Boost Converter design involves the selection of the inductors, the output capacitor, the power switches and the output diodes [8]. Both the inductors and diodes should be identical. In order to select these components, it is necessary to know the duty cycle range and peak currents. Since the output power is channelled through 'n' power paths where 'n' is the number of phases, a good starting point is to design the power path components using 1/n times the output power[8] .Basically, the design starts with a single boost converter operating at 1/n times the power. The design considerations of IBC are discussed in this section.

For an Interleaved Boost Converter, two phases are utilized since the ripple content reduces with increase in the number of phases [9]. Further increasing the number of the phases, without much decrease in the ripple content, the complexity of the circuit increases very much, thereby increasing the cost of implementation. Hence, as a trade-off between the ripple content and the cost and complexity, number of phases is chosen as two.

The gating pulses of the two phases are shifted by a phase difference of 360/n, where n is the number of parallel boost converters connected in parallel. For a two-phase interleaved boost converter n=2, which is 180 degrees.

The design of duty cycle is based on the number of phases. This is because, depending upon the number of phases, the ripple is minimum at a certain duty ratio. Hence with the required input and output value, the duty ratio is chosen to be as D=0.794.

The selection of capacitance and inductance is done using the formulae,

$$C = \frac{V_0 DF}{R \Delta V_0} \quad (3)$$

Where V_0 represents the output voltage (V), D represents the duty ratio (no unit), F represents Frequency (Hz), R represents Resistance (ohm) and ΔV_0 represents the change in the output voltage (V).

$$L = \frac{V_s D}{\Delta i_L F} \quad (4)$$

Where D represents the duty ratio (no unit), R represents Resistance (ohm), F represents frequency (Hz).

Power devices are used for lower cut-in voltage, higher reverse leakage current, higher operating frequency. MOSFET is used as a switching device since it is a voltage controlled device, having high gate circuit impedance. Since it has positive temperature coefficient, secondary breakdown does not occur.

DC-DC converter has plenty of chips available. Based on the specification, No RSENSE TM Current Mode Boost DC/DC Controller (LTC3872) is chosen[10]. The LTC3872 is a constant frequency current mode boost DC/DC controller that drives an N-channel power MOSFET and requires very few external components. The No RSENSE TM architecture eliminates the need for a sense resistor, improves efficiency and saves board space as demonstrated in “Linear Technology”. The circuit diagram of Interleaved Boost Converter and conventional boost converter are shown in Fig. 6.

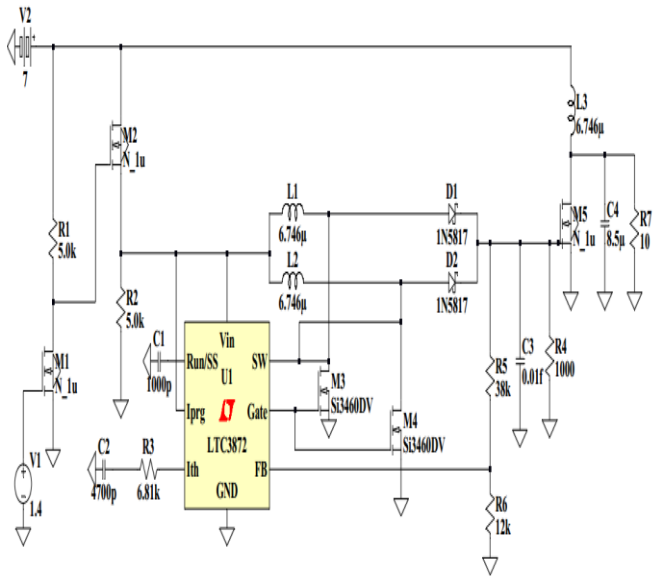

Fig. 6- Interleaved Boost Converter using LTC3872

The LTC3872 can be used either by sensing the voltage drop across the power MOSFET or by connecting the SW pin to a conventional sensing resistor in the source of the power MOSFET. Sensing the voltage across the power MOSFET maximizes converter efficiency and minimizes the component count. The RUN/SS pin controls whether the IC is enabled or is in a low current shutdown state. With an external capacitor connected to the RUN/SS pin an optional external soft-start is enabled.

Results and Discussion

The energy harvesting system designed for low power underwater applications are analyzed using LTspice simulator. For the analysis, the MFC is designed by considering stainless steel rod of 10cm as length as anode. Magnesium rod of 10cm is considered as cathode. A sample of sea water collected at Marina Beach (Chennai) is used as a source. The test is carried out in a small test tank (conical beaker). The voltage and current generated by the MFC is 1.01V and 1mA respectively using multi-meter. The setup used for the analysis is shown in Fig. 7.

It is observed that the MFC using sea water is able to generate more than 1V continuously which is more than sufficient for power management system which requires only 0.7V. The boost converter requires a minimum voltage of 1.4V for the Converter to turn ON.

Hence, the output produced from the MFC (0.7V - 1V) is increased to a voltage of 1.4V using Charge Pump as shown in Fig. 8.

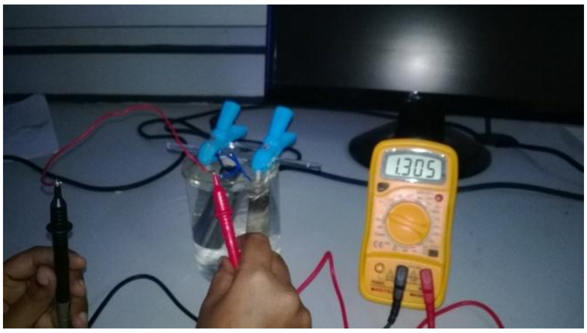

Fig. 7- Microbial Fuel Cell using sea water

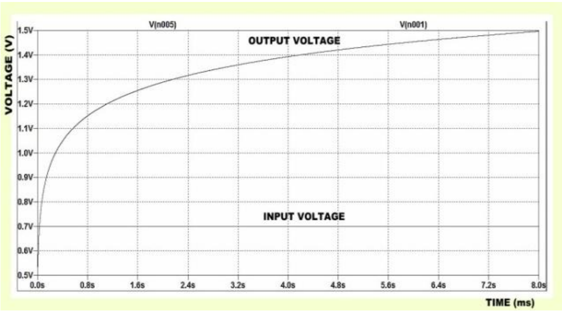

Fig. 8- Charge Pump

To maintain a constant voltage for continuous power supply, the supercapacitor is essential for storing the voltage of Charge Pump. The constant 1.4V stored by the supercapacitor using the design carried is shown in the Fig. 9

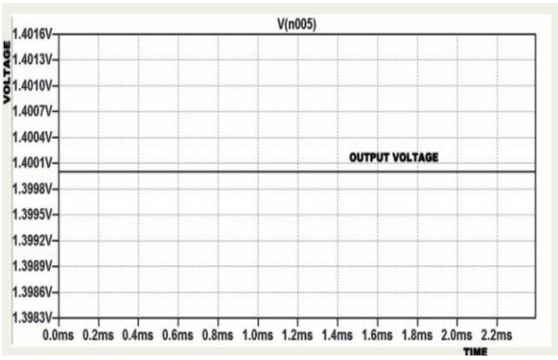

Fig. 9- Output voltage of Supercapacitor

The comparison between IBC and Conventional Boost Converter are carried in order to validate the best required for the underwater application devices. The various parameters considered for the analysis are shown in Table 1.

Table.1 Simulation Parameters

Parameters	Values
Input Voltage (V)	1.4
Switching Frequency(KHz)	50
Duty Ratio	0.794
Inductance, L (uH)	6.746
Capacitance, C (uF)	8.5
Resistance, R (Ohm)	10

The simulation results of the IBC and the Conventional Boost Converter are shown in the Figs. 9 - 14. The input and output voltage ripple, inductor current ripple and output current ripple of IBC are shown in the Figs. 10, 11 & 12.

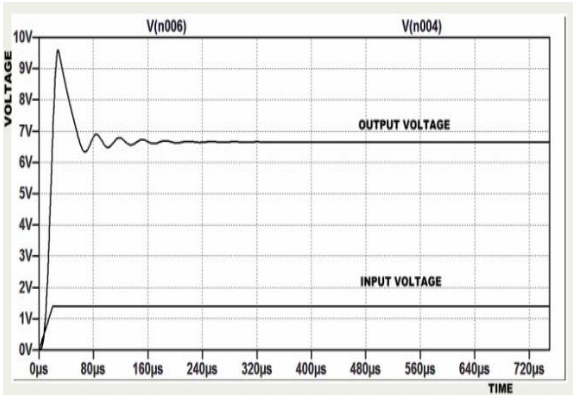

Fig. 10- Input and Output voltage of IBC

For a given input voltage of 1.4V, the output voltage produced by the IBC is 6.64 V as shown in Fig. 10. The number of phases (n) considered for the analysis is 2. Since two phases are considered, there is a 180 degree phase shift. Due to the charging and discharging of inductors, a ripple at the initial stage for the duration of 240us is observed and above 240us the voltage is maintained constant as shown in Fig. 10.

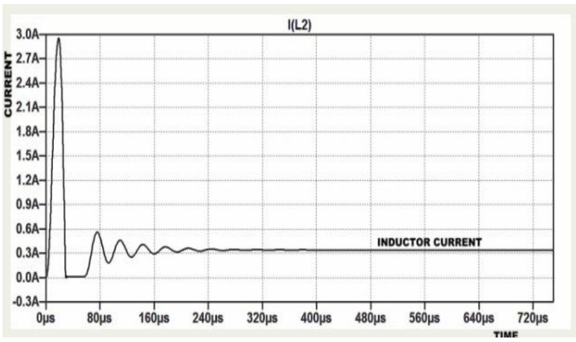

Fig. 11- Inductor current ripple of IBC

The ripples of the inductor and load current are shown in the Figs. 11 & 12. It is observed that the constant current of 0.339 A and 0.664 A is obtained after 240us respectively.

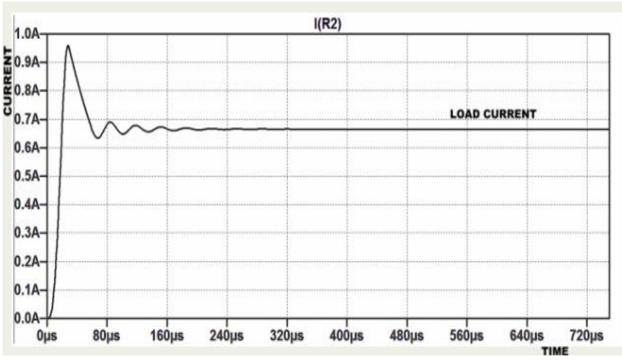

Fig. 12 -Load current ripple of IBC

The performance analysis of the Conventional Boost Converter by considering the same parameters listed in Table 1. The input and output voltage ripple, inductor current ripple and load current ripple of Conventional Boost Converter are shown in the Figs. 13, 14 & 15.

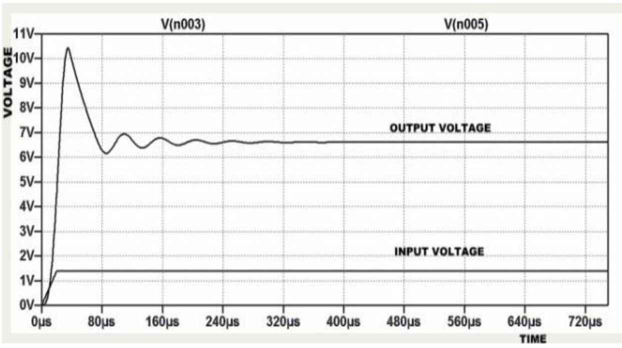

Fig. 13- Input and Output voltage of Boost Converter

For a given input voltage of 1.4V, the output voltage generated by the Conventional Boost Converter design is 6.59V as shown in the Fig. 13. Due to the charging and discharging of the inductor at the output, there is a ripple at the initial stage of 320us is observed and above 320us the voltage is maintained constant as shown in the Fig. 13.

The ripples of the inductor and load current are shown in the Figs. 13 & 14. It is observed that the constant current of 0.667A and 0.659A is obtained after 320us respectively.

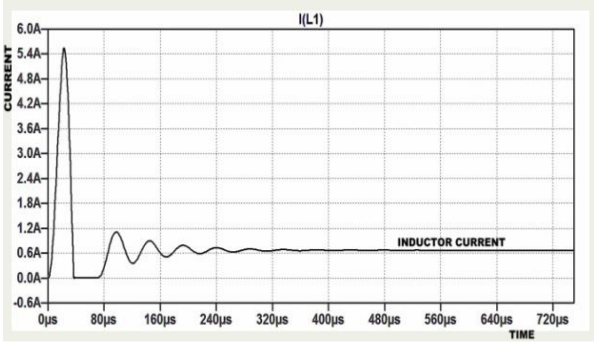

Fig. 14 Inductor current ripple of Boost Converter

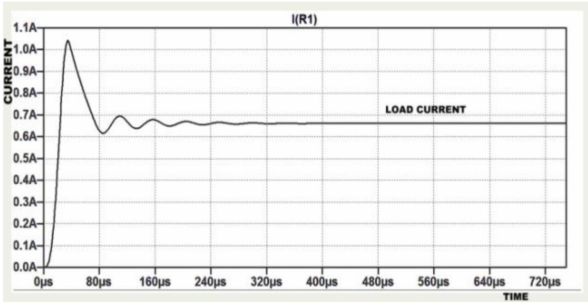

Fig. 15- Output current ripple of Boost Converter

The various parameter comparisons between Conventional Boost Converter and IBC is shown in Table 2. It is observed from the table that IBC reduces the number of ripples compared to Conventional Boost Converter. This result in stable output current required for the underwater application devices.

Table 2 Comparison between Conventional Boost Converter and IBC

Parameters	Boost Converter	IBC
Input voltage (V)	1.4	1.4
Output voltage (V)	6.59	6.64
Switching frequency (KHz)	50	50
Input current ripple	13.1 %	0.1226%
Output current ripple	1.13%	0.819%
Output voltage ripple	0.12%	0.07%

Comparison of IBC and Conventional Boost Converter using LTC3872

The comparison between IBC and Conventional Boost Converter using LTC3872 are carried in order to validate the best required for the underwater application devices.

The simulation results of the Interleaved Boost Converter and the Conventional Boost Converter using LTC3872 are shown in the Figs. 16 - 21. The input and output voltage ripple, inductor current ripple and output current ripple of Interleaved Boost Converter using LTC3872 are shown in the Figs. 16, 17 & 18.

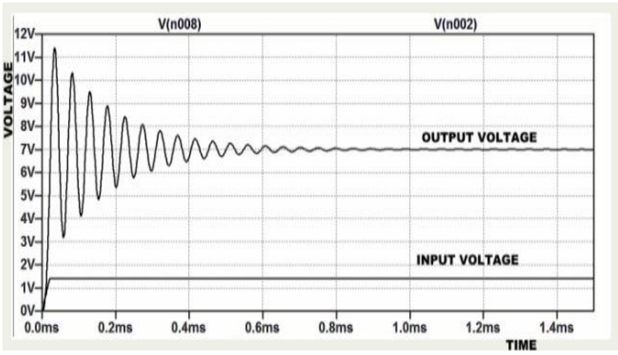

Fig. 16- Input and Output voltage of IBC using LTC3872

For a given input voltage of 1.4V, the output voltage produced by the IBC using LTC3872 is 7.02V as shown in the Fig. 10. Due to the charging and discharging of inductors, a ripple at the initial stage for the duration of 1.0ms is observed and above 1.0ms the voltage is maintained constant as shown in Fig. 16.

The performance analysis of the Conventional Boost Converter using LTC3872 by considering the same parameters listed in Table 1. The input and output voltage ripple, inductor current ripple and load current ripple of Conventional Boost Converter using LTC3872 are shown in the Figs. 19, 20 & 21.

The ripples of the inductor and load current are shown in the Figs. 17& 18. It is observed that the constant current of 1.85mA and 0.7A is obtained after 0.02ms and 1.0ms respectively.

For a given input voltage of 1.4V, the output voltage produced by the Conventional Boost Converter is 6.98V as shown in the Fig. 19 .Due to the charging and discharging off the inductor at the output, there is a ripple at the initial stage of 1.2ms is observed and above 1.2ms the voltage is maintained constant as shown in the Fig. 19.

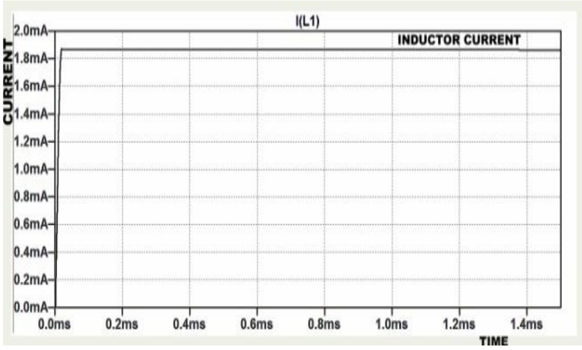

Fig. 17- Inductor current ripple of IBC using LTC3872

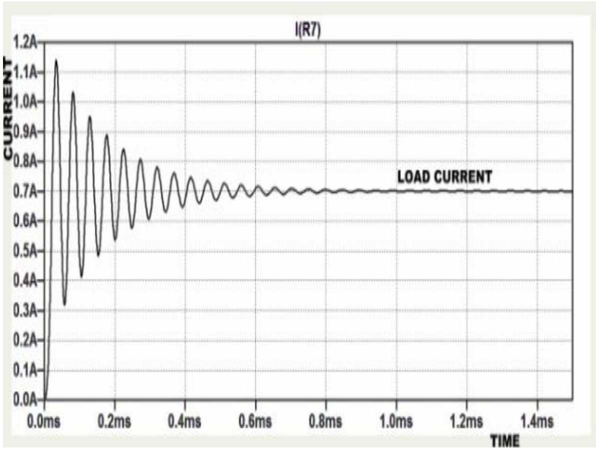

Fig. 18- Output current ripple of IBC using LTC3872

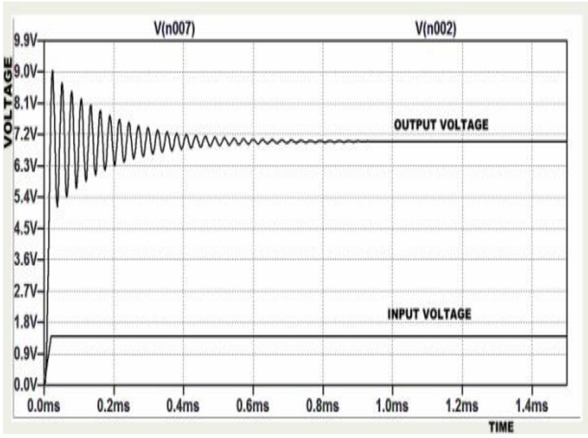

Fig. 19- Input and Output voltage of Boost Converter using LTC3872

The ripples of the inductor and load current are shown in Figs. 20& 21. It is observed that the constant current of 3.62mA and 0.69mA is obtained after 0.03ms and 1.2ms respectively.

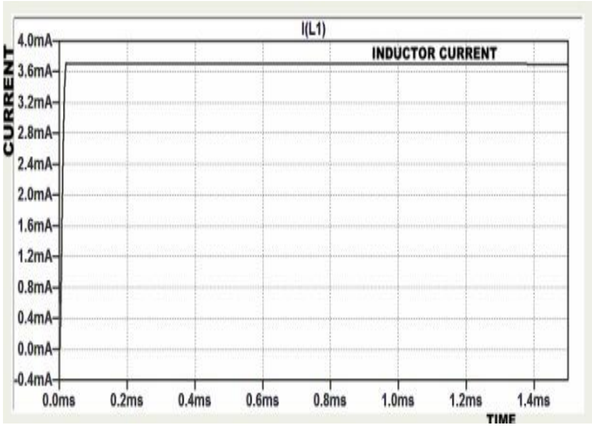

Fig. 20- Inductor current ripple of Boost Converter using LTC3872

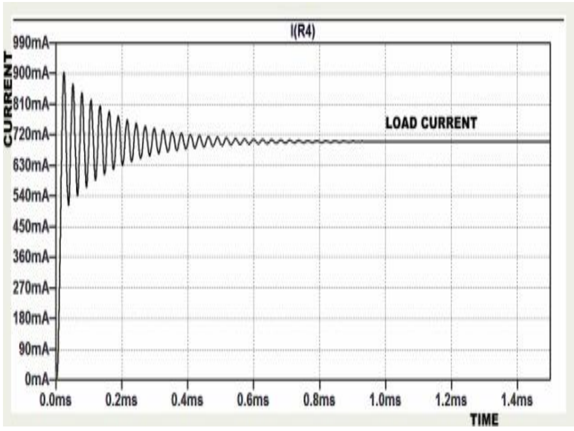

Fig. 21- Output current ripple of Boost Converter using LTC3872

The various parameter comparisons between IBC and Conventional Boost Converter is shown in the Table 3. It is observed from the table that IBC with and without using LTC3872 generates more voltage compared to Conventional Boost Converter with and without using LTC3872. This result in stable output voltage required for underwater application devices.

Conclusion

In this paper, an underwater energy harvesting system is designed. The energy harvesting system consists of MFC and power management system. The analysis of the energy harvesting system is performed using LTspice. From the analysis, it is observed that the designed IBC with and without using LTC3872 produces an output voltage of 7.02V and 6.64V compared to conventional boost converter. Further the designed energy harvesting system will be implemented in hardware for real time analysis.

Table 3 Simulation results of Conventional Boost Converter and Interleaved Boost

Converter Type	Output Voltage (V)	
	Without LTC 3872	With LTC3872
Conventional Boost Converter	6.59	6.98
Interleaved Boost Converter	6.64	7.02

References

1. John G. Proakis, Ethem M. Sozer, Joseph A. Rice and San Diego Milica Stojanovic, Shallow Water Acoustic Networks, *IEEE Communications Magazine*, 39 (2001), 114-119.
2. John Heidemann, Wei Ye, Jack Wills, Affan Syed, Yuan Li, Research Challenges and applications for Underwater Sensor Networking, *Wireless Communication and Networking Conference*, l1(2006), 228-235.
3. Meehan. A, Hongwei Gao, Lewandowski. Z, Energy Harvesting with Microbial Fuel Cell and power management system, *IEEE transactions on power electronics*, 26 (2011),176-181.
4. Meehan.A, Hongwei Gao, Lewandowski.Z, Energy harvest with Microbial Fuel Cell and power management system, *Energy Conversion Congress and Exposition (ECCE), IEEE*, 2 (2009), 3558-3563.
5. Guoxian Huang, Ridvan Umaz, Udayarka Karra, Baikun Li and Lei Wang, 2013, A Biomass-based Marine Sediment Energy Harvesting System, *Low Power Electronics and Design (ISLPED)*, (2013), 359-364.
6. Jae-Do Park, Zhiyong Ren, 2011,Efficient Energy Harvester for Microbial Fuel Cells using DC/DC converters, *Energy Conversion Congress and Exposition (ECCE)*,(2011), 3852-3858.
7. Gaetano Palumbo and Domenico Pappalardo, Charge Pump Circuits: An Overview on Design Strategies and Topologies, *IEEE Circuits and System Magazine*, 10 (2010), 31-45.
8. J.S. Anu Rahavi, T.Kanagapriya, Dr.R.Seyezhai, Design and analysis of Interleaved Boost Converter for Renewable Energy source, *International Conference, Computing, Elecronics and Electrical Technologies (ICCEET)*, (2012), 447-451.
9. Mounica Ganta, Pallam reddy Nirupa, Thimmadi Akshitha, Seyezhai. R, Simple and efficient implementation of Two-Phase Interleaved Boost Converter for renewable energy source, *International Journal of Emerging Technology and Advanced Engineering*, 2(2012), 676-681.
10. Linear Technology, No RSENSE Current Mode Boost DC/DC Controller, *LTC3872 Datasheet*, 1992.