A Comparative Study on Single Switch and Quadratic Buck-Boost Converters

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Abstract-*Conventional voltage regulators are less capable of providing high voltage gain in an efficient manner for applications demanding steady dc voltage. The switching frequency of the power converter must be increased in order to achieve small size, light weight, and low noise. Many new converters which are modifications of the conventional voltage regulators are being proposed inorder to improve the converter performance characteristics. A comparative study on such converters are helpful in selecting the most suitable converter for a particular application. Here, the converters taken for comparison are quadratic buck-boost converter and single switch buck-boost converter. Both the converters are individual based on ripple factor, power density, and output voltage with same switching frequency, duty ratio and input voltage. The simulation of both the converters were performed using MATLAB/Simulink. The variation of output voltage with respect to duty ratio and output ripple with respect to switching frequency of both converters were tabulated and plotted. The prototype of 20kHz, 5W of single switch buck-boost converter was implemented using PIC16F877A microcontroller and the simulation results were compared.*

Keyword- *Single Switch Buck-Boost Converter, Quadratic Buck-Boost Converter, Voltage gain,* Switch Stress.

I. INTRODUCTION

In recent years, the usage of renewable energy systems such as fuel cell and photovoltaic systems are encouraged due to various environmental troubles caused by other fuels, such as climate change and global warming by increased emissions of carbon dioxide. With increasing attention to environmental problems, energy achieved from the fuel cell systems is focused on the low environmental effects and clean energy. Fuel cells are an effective alternative to replace fuels in emergency power systems and vehicles. Fuel cells can be used as clean energy by users with low emissions of carbon dioxide. Due to steady operation with renewable fuel supply and high effectiveness and effciency, the fuel cell has been recognized increasingly as a suitable alternative source. There are some problems of this fuel such as high cost, but they have brilliant features such as high effciency

and small size. The output voltage of the fuel cell unit is low and is not steady and it cannot be directly connected to the load. For applications that need a steady DC voltage, buck-boost DC-DC converter is required so as to obtain an incremented or decremented voltage at the output compared to the input.

However, the traditional buck-boost converter is not suitable for fuel cell sources. The traditional buck-boost converter efficiency is expected high, however, it is low and is limited by the effects of diodes, switches and equivalent series resistance (ESR) of capacitors and inductors. In order to obtain the high efficiency and high voltage gain, many converters, which are modifications of conventional buck-boost converters have been suggested by various researchers inorder to attain more and more efficient converters with low cost. A multiwinding coupled inductor and a voltage doubler can be used to achieve high step-up voltage gain [1]. But the leakage inductance of the coupled inductor is so important that it cause high voltage spikes and adds the voltage stress. Also, the voltage spike of the main switch is limited and voltage stress can be adjusted by the turns ratio of the coupled-inductor. Converter with switched capacitor techniques with capacitors on the output-stacking which are charged in parallel and discharged in series are also employed to achieve high step-up gain [2].

A comparison of these types of converters are very much beneficial so that we can select the most efficient converter for a given application. The two circuits taken for comparison are quadratic buck-boost converter and single switch buck-boost converter. Both converters are compared on the basis of parameters such as output voltage with respect to duty ratio, Output voltage ripple, number of components and switching stress. The quadratic buck boost converter consists of two switches whereas in the other circuit, there is only a single switch. Thus, it is easy to identify the advantages of each converters and can select them for suitable applications.

II. SINGLE SWITCH AND QUADRATIC BUCK-BOOST CONVERTERS

Here, Single switch buck-boost converter and quadratic buck-boost converter are compared based on various factors.
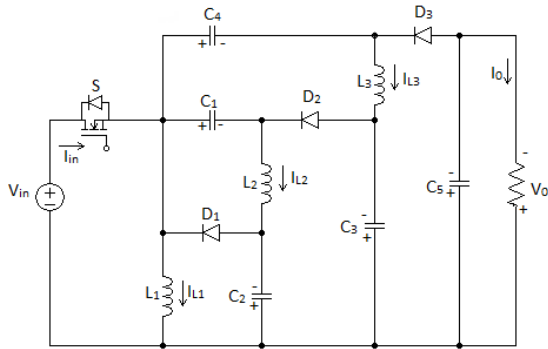
Single Switch Buck-Boost Converter

Fig.1: Circuit diagram of single switch buck-boost converter

Principle of Operation

This converter consists of one power switch S, three diodes D_1, D_2, D_3, three inductors L_1, L_2, L_3, ve capacitors C_1, C_2, C_3, C_4, C_o and load R. Certain assumptions are taken for the analysis of this circuit.

- The capacitors in this converter are large enough, hence the voltage across capacitors are assumed to be constant.
- The main switch of the converter is treated as ideal and the parasitic capacitor of the main switch is neglected.

There are two modes of operation for this converter in continuous conduction mode(CCM). The duty ratio can be varied so as to obtain the required voltage gain and output voltage. The input current of the converter is discontinuous. Here, the input current and the switch current are the same. The output voltage of the converter is negative as in a conventional buck-boost converter. This converter operates as a universal power supply and it is appropriate for low voltage and low power applications.

Mode 1
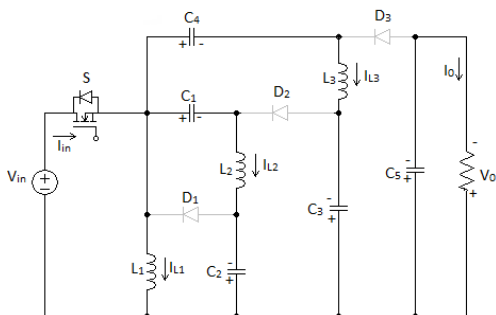
Fig.2 Equivalent Circuit during Mode 1.

During mode 1, the switch S is turned on and the diodes D_1, D_2 and D_3 are turned off. The inductors L_1, L_2 and L_3 are magnetized linearly. The capacitors C_1 and C_4 are charged by the capacitors C_2 and C_3.

$$V_{L1} = V_i \tag{1}$$

$$V_{L2} = V_{C2} - V_{C1} + V_i \tag{2}$$
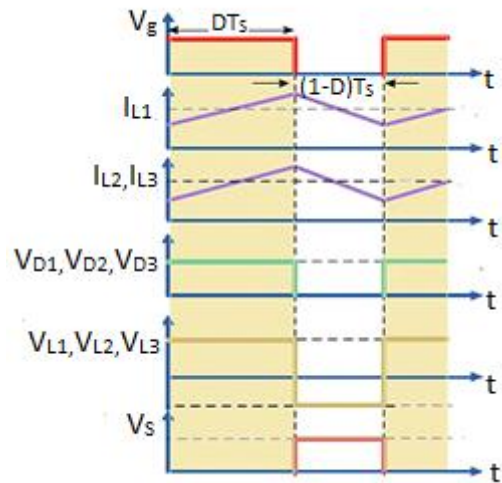
$$V_{L3} = V_{C3} - V_{C4} + V_i \tag{3}$$
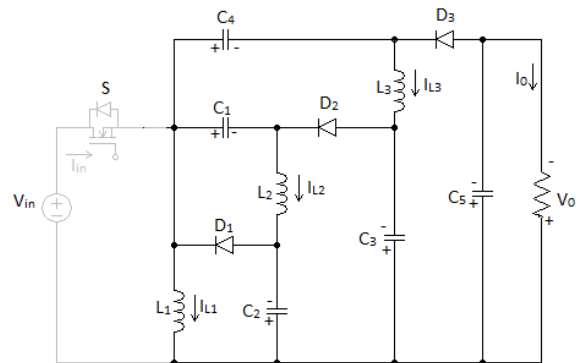

Fig. 3: Waveforms (Mode 1 shaded)

Mode 2

Fig. 4: Equivalent circuit during Mode 2

During mode 2, the switch S is turned off and the diodes D_1, D_2 and D_3 are turned on. The inductors L_1, L_2 and L_3 are demagnetized linearly. The capacitor C_2 is charged by the inductor L_1 and the capacitor C_3 is charged by the inductors L_1 and L_2 and the capacitors C_1 and C_4 are discharged.

$$V_{L1} = -V_{C2} \tag{4}$$

$$V_{L2} = V_{C2} - V_{C3} \tag{5}$$
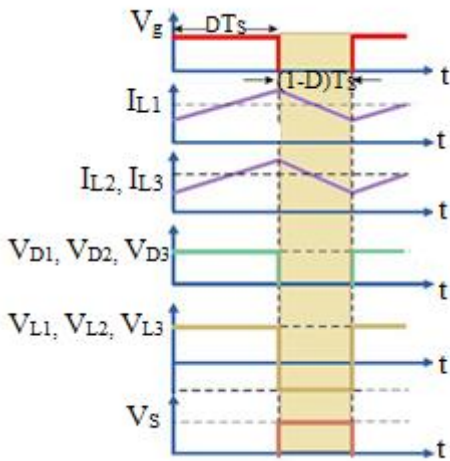
$$V_{L3} = V_{C1} - V_{C4} \tag{6}$$

Fig. 5: Waveforms (Mode 2 shaded)

By applying volt-sec balance principle on inductors L_1, L_2 and L_3, we can obtain the voltage transfer ratio in CCM as:

$$\frac{V_O}{V_i} = \frac{3 \times D}{1 - D} \qquad (7)$$
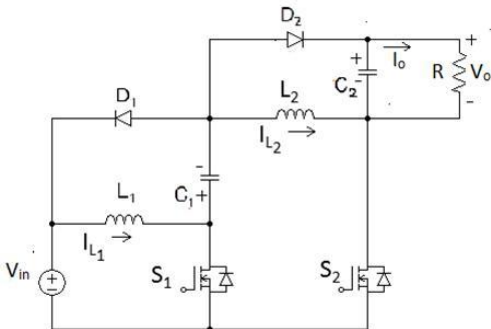
A.   *Quadratic Buck-Boost Converter*

Fig. 6: Circuit diagram of quadratic buck-boost converter

Principle of Operation

It consists of two diodes, D_2, two inductors L_1, L_2, two capacitors C_1, C_2 and two switches S_1 , S_2. The two switches in the circuit are turned on simultaneously so that there is no phase delay between them. There are two modes of operation for this circuit.

The inductors acts as the medium for storing and transferring energy. By applying volt-sec balance principle,

$$\frac{V_O}{V_i} = \frac{D^2}{(1 - D)^2} \qquad (8)$$

Mode 1
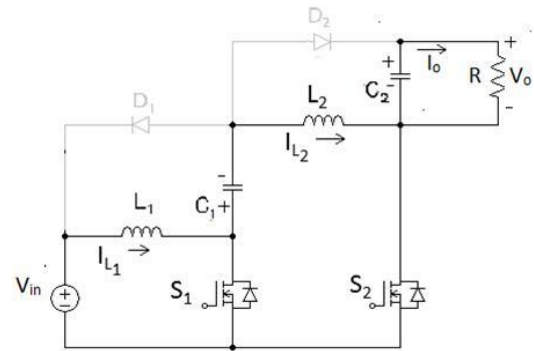
Fig. 7: Equivalent Circuit during mode 1

In this mode, S_1 and S_2 are turned on simultaneously which makes D_1 and D_2 be reversely biased. L_1 stores the energy by the input voltage source. L_2, stores the energy while C_1 is being discharged and C_2 is supplying the load.

$$V_{L1} = V_{in} \qquad (9)$$
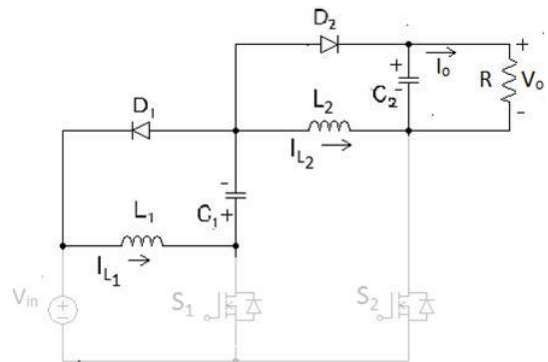
$$V_{L2} = V_{C1} \qquad (10)$$

Mode 2

Fig. 8: Equivalent Circuit during mode 2

In this mode, S_1 and S_2 are turned off simultaneously. The diodes D_1 and D_2 are forward biased. The inductors L_1 and L_2 transfers the energy stored in them during this interval thereby charging C_1 and C_2 respectively.

$$V_{L1} = V_{C1} \qquad (11)$$

$$V_{L2} = V_0 \qquad (12)$$

III. SIMULATION MODELS AND RESULTS

The simulation of single switch buck-boost converter is performed in MATLAB/Simulink 2014. The detailed simulink model is shown in figure 9.

Simulation Parameters of Single Switch Buck-Boost Converter are given in table 1.

Table 1: Simulation Parameters of Single Switch Buck-Boost Converter

Parameter	Value
DC Voltage	11 V
Inductance, L_1	1 mH
L_2, L_3	580 μH
Capacitance, C_1, C_2, C_3, C_4	100 μF
C_O	470 μF
Switching frequency	37 kHz
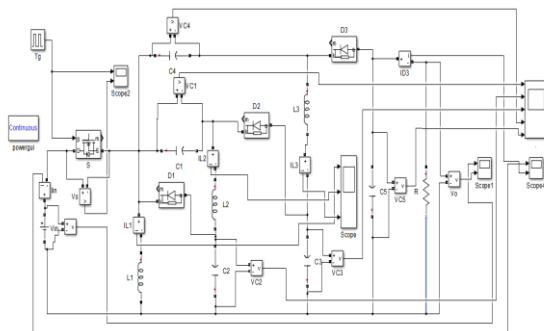
Fig. 9: Simulink Model of Single Switch Buck-Boost Converter

Simulation is performed with 11 V input DC source and a 100Ω resistive load. The current through inductors and voltage across capacitors are measured.

Simulation Results of Single Switch Buck-Boost Converter are shown below:
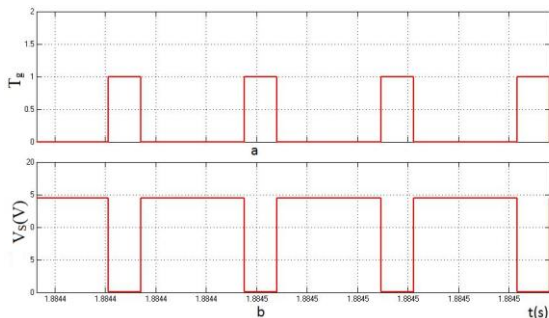
Fig. 10. (a)gate pulse (b)voltage across switch in buck operation.
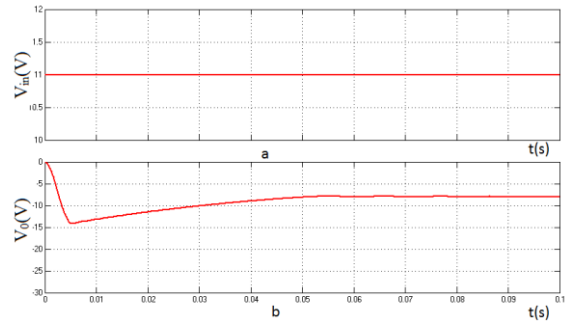
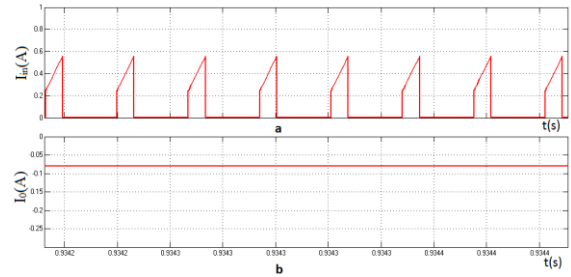Fig. 11. (a)input voltage (b)output voltage in buck operation.

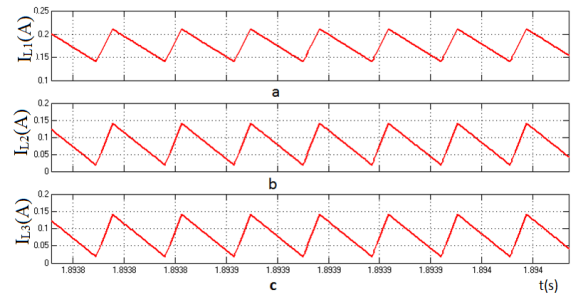Fig. 12. (a)input current (b)output current in buck operation.

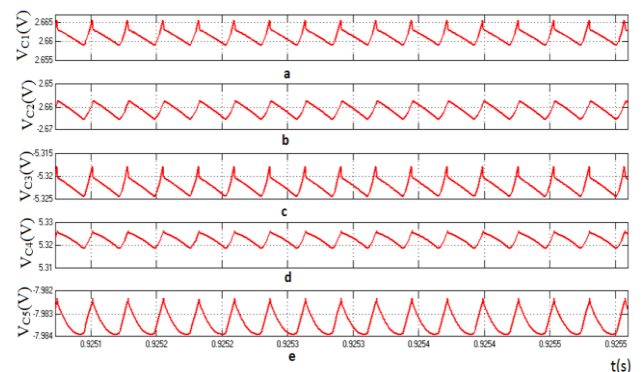Fig. 13: Current through (a)L_1, (b)L_2, (c)L_3 in buck operation

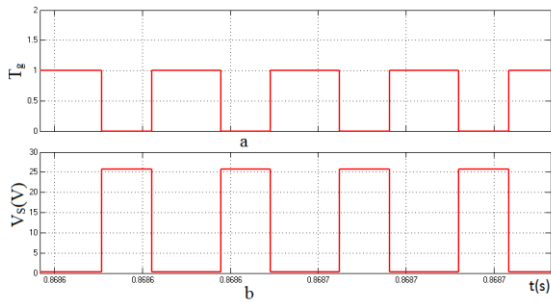Fig.14 :Voltage across (a)C_1, (b)C_2, (c)C_3, (c)C_4, (d)C_5 in buck operation

Fig. 15. (a)gate pulse (b)voltage across switch in boost operation
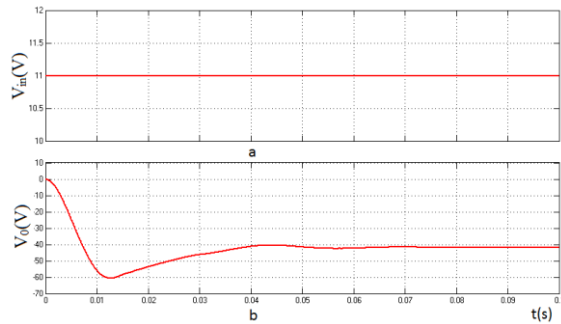

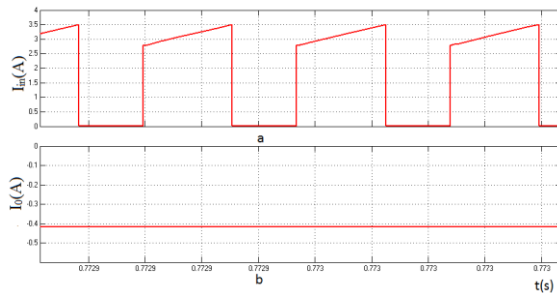Fig. 16. (a)input voltage (b)output voltage in boost operation

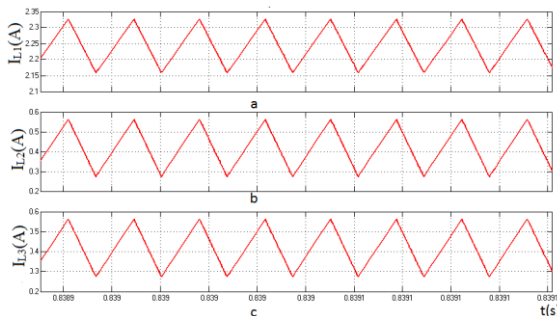Fig. 17. (a)input current (b)output current in boost operation.

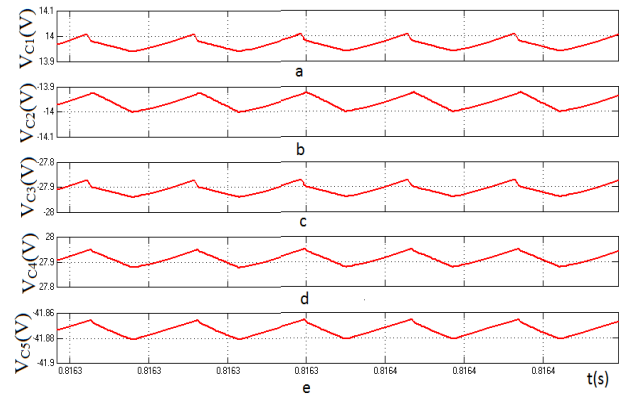Fig. 18: Current through (a)L_1, (b)L_2, (c)L_3 in boost operation

Fig.19 :Voltage across (a)C_1, (b)C_2, (c)C_3, (c)C_4, (d)C_5 in boost operation

Simulation Parameters of quadratic buck-boost converter are shown in table 2.

Table 2: Simulation Parameters of Quadratic Buck-Boost Converter

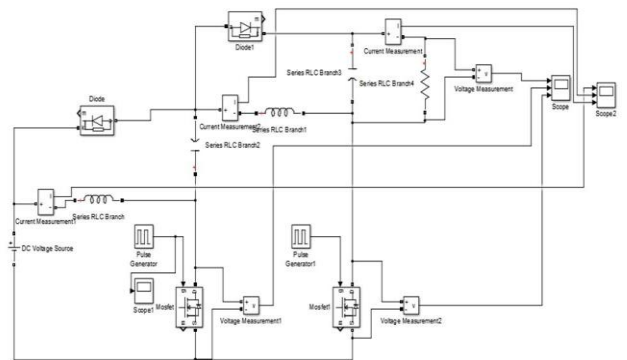| Parameter	Value
DC Voltage	11 V
Inductance, L_1	1 mH
L_2	2 mH
Capacitance, C_1, C_2	47μF
Switching frequency	32 kHz

Fig. 20: Simulink Model of Quadratic Buck-Boost Converter

Figure 20 shows the simulink model of the quadratic buck-boost converter. Simulation is performed with 11 V input DC source and a 100Ω resistive load.

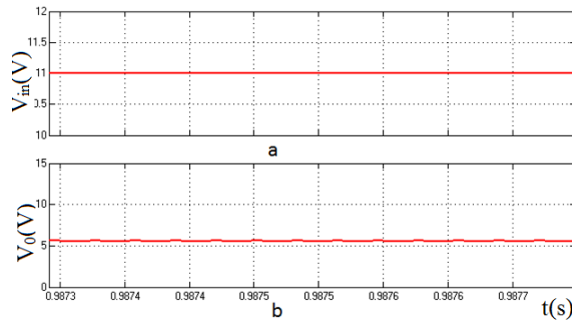Simulation results of quadratic buck-boost converter are shown below:

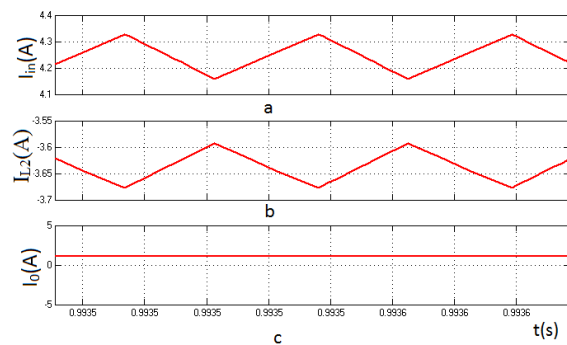Fig.21: (a)Input Voltage, (b)Output Voltage in buck operation

Fig.22: (a)Input current, (b)current through L_2, (c)Output Current in buck operation
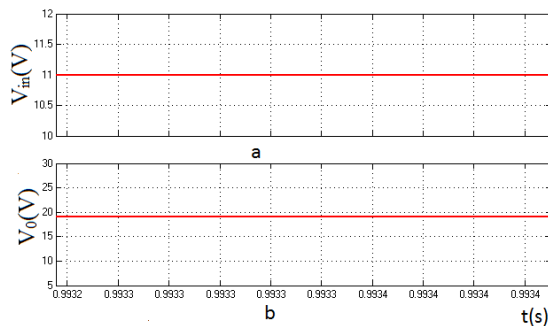

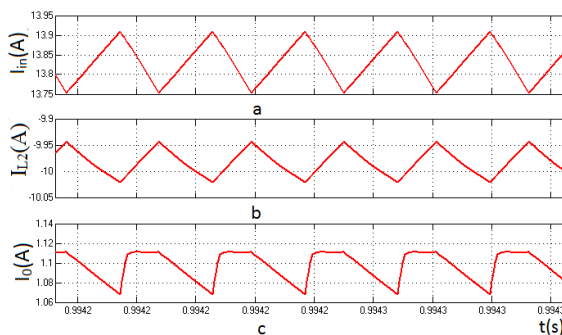Fig.23: (a)Input Voltage, (b)Output Voltage in boost operation

Fig.24: (a)Input current, (b)current through L_2, (c)Output Current in boost operation

IV. COMPARISON OF SINGLE SWITCH AND QUADRATIC CONVERTERS

Table 3 : Comparison of various parameters

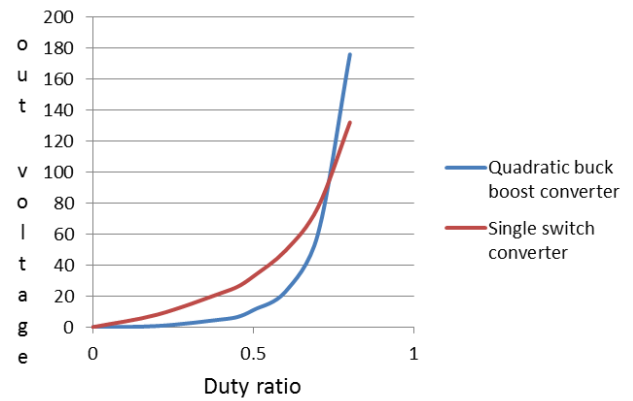| Parameters	Quadratic Converter	Single Switch Converter
Number of switches	2	1
Number of Inductors	2	3
Number of diodes	2	3
Number of Capacitors	2	5
Number of Components	8	12
Voltage gain	$D^2/(1-D^2)$	$3D/(1-D)$
Output Voltage Ripple	High	Low
Switching Losses	High	Low

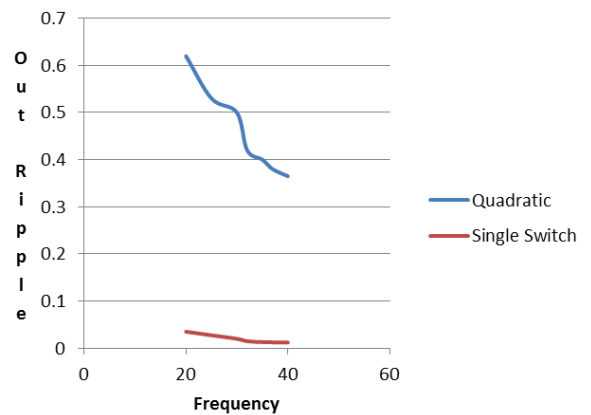Fig:25 Output voltage v/s duty ratio of both converters

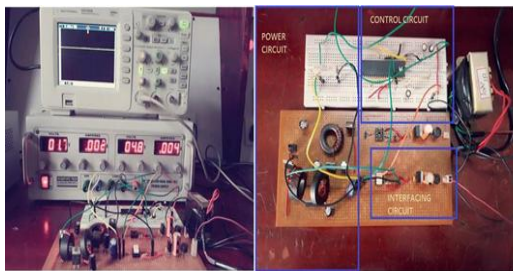Fig:26 Output ripple v/s frequency of both converters

Fig.27: Experimental Setup

A prototype of 20kHz, 5W of single switch buck-boost converter was setup in lab. The output voltage waveforms in both buck and boost mode operations were observed in digital storage oscilloscope(DSO).
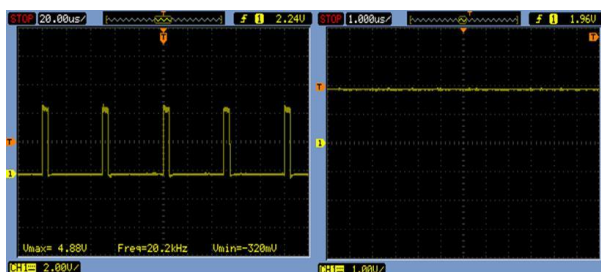

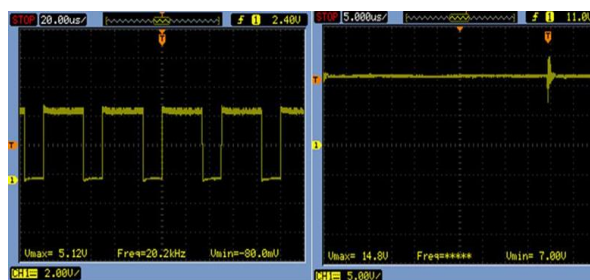
Fig. 28: Gate pulse and output voltage in buck operation

Fig.29: Gate pulse and output voltage in boost operation

VI. CONCLUSIONS

The single switch buck-boost converter and quadratic buck boost converters are essentially the modifications of conventional buck-boost converter with improved performance characteristics. Both these converters were compared on the basis of parameters like switching stress, number of components and graphs were plotted for output voltage with respect to duty ratio and output voltage ripple with respect to switching frequency. The single switch buck-boost converter gives better performance than the quadratic buck boost converter in the way of less ripple voltage and high output voltage in the range of operating duty ratio and frequency. For a switching frequency of 37kHz and 0.58 duty ratio, the quadratic buck-boost converter

provides only 20 V as output whereas single switch converter provides an output voltage of magnitude 42 V for the same input voltage of 11 V. The control circuit for single switch converter is simple since there is only one switch. But the complexity of single switch converter is slightly more due to the presence of more number of components. A 20kHz, 5W prototype of single switch buck-boost converter was implemented using PIC16F877A microcontroller. For an input voltage of 11 V, about 2 V was obtained in buck operation and for an input voltage of 2.7 V, an output voltage of 11 V was obtained in boost operation and these results were matching the results obtained from the simulation of prototype of the converter.

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