Design and Analysis of Passive LC3 Star Component Buck Converter

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Research Article

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Abstract

A comprehensive analysis on a novel LC^3 star Buck converter is introduced in this paper. DC-DC, AC-DC and closed loop topology of the designed converter is examined. The analysis verifies the improvement done due to the implementation of the LC^3 star arrangement. Efficiency of the proposed DC-DC converter has a maximum efficiency of 96.71%. For AC-DC, maximum efficiency is 97.47%. LC^3 arrangement also improves the power and THD of the proposed AC-DC converter. To further improve the THD, a closed loop analysis is also done. Simulations are done by using PSIM software. A 10V prototype is made, which shows similar results with the theoretical analysis.

I. Introduction

Power electronics is a significant part of various phases regarding numerous devices and systems. Usually, this specific part of Electronics Engineering is dedicated to convert electrical energy of one genre to another consisting different characteristics [1]. These days, a wide range of appliances are being used which requires a unique amount of electrical energy as per constructional issue. The driving energy may differ from the primary supply power. This is the particular area where converters step in. The converters can convert AC or DC supply to the required form of electrical supply with required specifications [2] [3] [4].

A converter is designed in such a way that it only accepts DC or AC input and produce optimized desired output with different voltage level and features for a specific load [5]. The process is accomplished by designing the circuit with both inductive and capacitive filter elements which initiate the high frequency switching [6] [7]. A converter is used for different purpose like manipulating the magnitude, inverting the input polarity or for the production of several output at a time [8] [9]. Converters operates as the transforming bridge in between the input and output. These are highly used for power regulation and conversion, control circuits for dc motors, power supply for computers etc [10] [11] [12].

Buck converters are step-down converters, which are used to lower the output voltage compared to input voltage [13] [14]. The average currents also diploid on the process. It operates on Switched-Mode Power Supply (SMPS) topology [15] [16]. This type of switching converters can showcase higher power efficiency then the simple linear regulators. In the basic operation all the components are assumed to be ideal with no system loss [17] [18]. Though practically, the models are being designed keeping some principal factors in mind i.e., the capacitance of the output capacitor (capable enough to supply power to the load), ensuring minimal commutation losses in switches and diodes, zero diode voltage in forward bias operation etc. [19] [20] [21]. The working principal of Buck converters is quite similar to Pulse Width Modulation (PWM) dimming which associates a small duty cycle and low average voltage in case of small load and vice-versa [22] [23] [24]. Usually the switches are placed on high side MOSFET as similar NPN bipolar may not be suitable unless a bootstrapped gate driver is included. The capacitor value is being manipulated as per the voltage ripple in the output [25] [26] [27]. LC filters are appreciated instead of RC filters. RC filters may result in limited current along with heat loss. On the other hand, the inductor

(L) in the LC filters establish a stable current flow and the voltage is also kept fixed with the capacitor (C) [28].

Conventional Buck converter experience problems which affect the efficiency of the converter. Due to current ripples electromagnetic interference increases, along with lower power factor and higher total harmonic distortion (THD) [29] [30]. PFC solution is used to overcome such problems. Hence in this paper, a comprehensive analysis on Buck converter is done by integrating the LC^3 star topology. The LC^3 star significantly improves the performance of the Buck converter for both DC-DC and AC-DC arrangement. To further improve the THD and power factor, analysis with a PI controller is also discussed.

Section II shows the proposed configuration of the converter, followed the circuit operation. Results are discussed in Section IV.

Ii. Proposed Circuit Configuration

Figure 1 illustrates the circuit diagram of the proposed converter. The proposed converter consists of DC input source Vs, the LC^3 star topology, made up of one inductor (L_1) and three capacitors (C_1, C_2, C_3), a MOSFET M_1, a diode D_1, an inductor L_2 and a filter capacitor C_4, parallel connected with the load. For an AC-DC topology, a bridge rectifier is placed before the LC^3 star topology. The AC-DC arrangement is shown in Fig. 2. The closed loop topology of the proposed converter is illustrated in Fig. 3. A PI controller is used for the closed loop topology.

Iii. Operation Of The Proposed Converter

The proposed converter’s working principle is depicted in Fig. 4. The designed converter works on two modes. Mode 1, when the switch is turned on (T_{on}) and Mode 2 when the switch is turned off (T_{off}). During T_{on} operation, the switch M_1 is turned on. Current flows through the LC^3 star topology and flows through inductor L_2 charging it. The current will not flow through diode D1 as it is reverse biased. During T_{off} operation, the switch is turned off. During this mode capacitors C_1-C_3 are charged. Inductor L_2 discharges and current flows though capacitor C_4, load R_1 and diode D_1.

Iv. Simulation Results

The designed circuit is simulated using PSIM software and its performance is compared with conventional Buck converter. For simulation, the following assumptions were made:

Frequency = 5000 Hz

L_1 = 1mH

L_2 = 5mH

$C_1 = C_2 = C_3 = 1uF$

$C_4 = 330uF$

$R_1 = 100\Omega$

A. DC-DC Topology

Output voltage of the proposed converter AT 50% duty cycle is shown in Fig. 5.

1. Efficiency Comparison

Efficiency comparison between proposed and convention Buck converter is shown in Fig. 6. From the graph it can be observed that the proposed converter has better efficiency when compared with the conventional converter. With increase in duty cycle, the efficiency of LC^3 star Buck converter increases and peaks at 96.71%.

2. Load Analysis

From the following graph, it can be observed that efficiency follows a decreasing linear function with respect to output resistance, for the DC-DC topology of the proposed LC3 Buck converter. As resistance increases, the value of efficiency decreases. The relation closely follows the following equation.

$$y = -0.0182x + 95.3$$

3. Frequency Analysis

Figure 8 shows the frequency analysis of the proposed DC-DC converter at 50% duty cycle. Increasing switching frequency increases switching loss. Increase in switching loss results in decrease in output power. Thus efficiency also decreases. Minimum efficiency of the converter can be observed at frequencies 5 kHz and 15 kHz, this decreasing trend in efficiency can be observes

B. AC-DC Topology

The following figure shows the output voltage of the AC-DC topology at 50% duty cycle.

1. Efficiency comparison

Figure 10 shows the efficiency comparison between AC-DC topology of the proposed converter and conventional Buck converter. From the graph below it can be observed that the efficiency of the proposed converter is better than conventional Buck converter. Efficiency of the converter increases with duty cycle. The efficiency of the proposed converter increases and stabilizes around 97%.

2. Power Factor Comparison

The power factor comparison between proposed and conventional Buck converter is shown in Fig. 11. From the graph it can be observed that the proposed converter has better power factor when compared with conventional Buck converter. With increase in duty cycle, power factor of the proposed converter also increases and peaks at 0.7076.

3. THD Comparison

The following graph shows the total harmonic distortion (THD) of the proposed converter and conventional Buck converter. From the graph it can be seen that the THD of the proposed converter is much lower when compared with the conventional converter. However the THD is still much higher to be considered standard. Thus further improvement is made upon the converter.

C. Improvement of THD with L_2

From the diagram below it can be observed that the THD% of the AC-DC topology of the proposed converter decreases with increase in duty cycle. However the THD% is still way above the standard value. Thus further improvement is made by varying the L_2 value. Figure 13 shows the relation between THD% and L_2 value. From the graph it can be observed that the value of THD% decreases with increase in L_2. The THD% has the lowest value of 63.62% at 45mH.

D. Closed Loop Topology

Table. 1 shows the comparison between closed loop and open loop topology. From the table it can be observed that the controller significantly improves the performance of the AC-DC proposed converter. The comparison is done by taking the best data from open loop topology. The table shows that THD% is improved from 63.62–29.85%, Power factor value increased from 0.7076 to 0.916 and efficiency increased from 97.47–98.25%. Overshoot of output voltage is significant reduced by the controller as shown in Fig. 11.

Table 1
Comparison between closed and open loop

	Efficiency	**THD %**	**Power Factor**
Closed loop	98.25	29.85	0.916
Open loop	97.47	63.62	0.7076

E. Comparison between rippled and iunrippled source

The efficiency comparison between rippled and unrippled DC source is shown in Fig. 15. From the graph below, it can be observed that the efficiency of the converters increases with increase in duty cycle. Efficiency of the rippled DC source is slightly higher than unrippled source. The efficiency of the rippled and unrippled sourced converters peaks at 97.47 and 96.71 respectively.

F. Experimental Verification

A prototype of the designed converter is made with an input voltage of 10V. The operation of the MOSFET is controlled by square wave signal generated by a signal generator. Figure 13 shows the output voltage waveform of the proposed DC converter at 80% duty cycle, in channel 2. From the following figure, it can be observed that at 80% duty cycle the converter has an average voltage of 9.2V. The following table shows the output voltage comparison between experimental and theoretical results.

	Output voltage (V)
Experimental result	9.2
Theoretical result	9.9

V. Conclusion

A new LC3 star Buck converter is proposed in this study. The proposed topology improves the performance of the DC-DC Buck converter. Similar improvement is also observed in AC-DC Buck converter. The LC3 arrangement significantly improves the converter. The star arranged capacitors improves the power factor, whereas the inductor improves the THD. Further improvement in THD is made by varying the Buck inductor. A closed loop analysis is also done to further augment the THD of the AC-DC converter. The DC-DC topology of the proposed converter has maximum efficiency of 96.71%, whereas the AC-DC topology has 97.47%. A 10V experimental prototype is made to verify the theoretical analysis.

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Figures

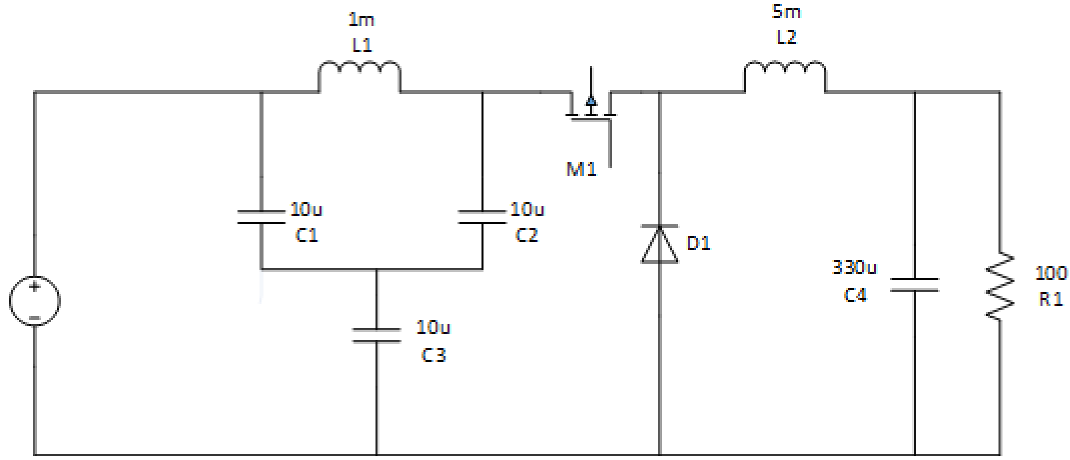


Figure 1

Proposed converter

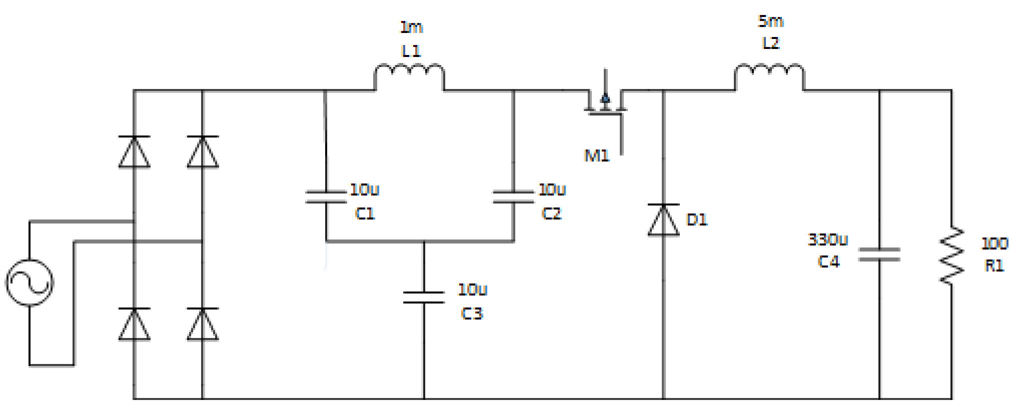


Figure 2

AC-DC topology of the proposed converter

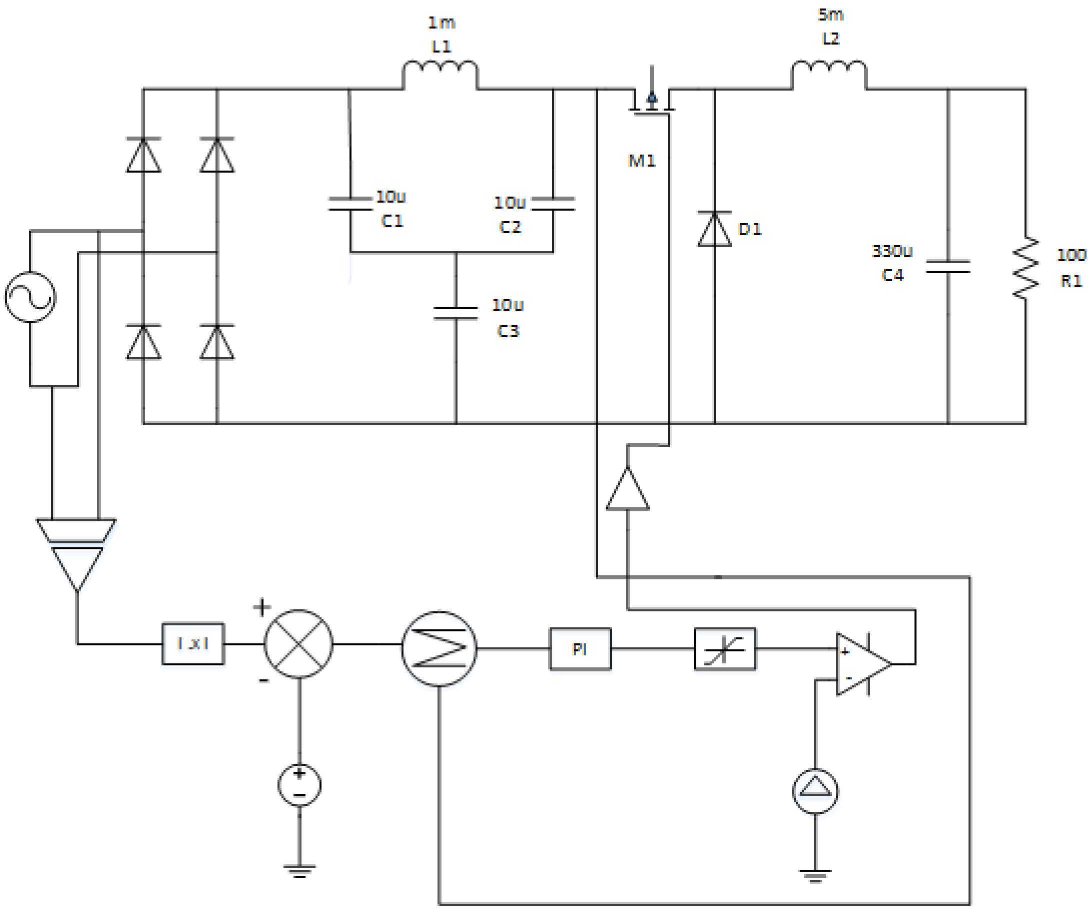
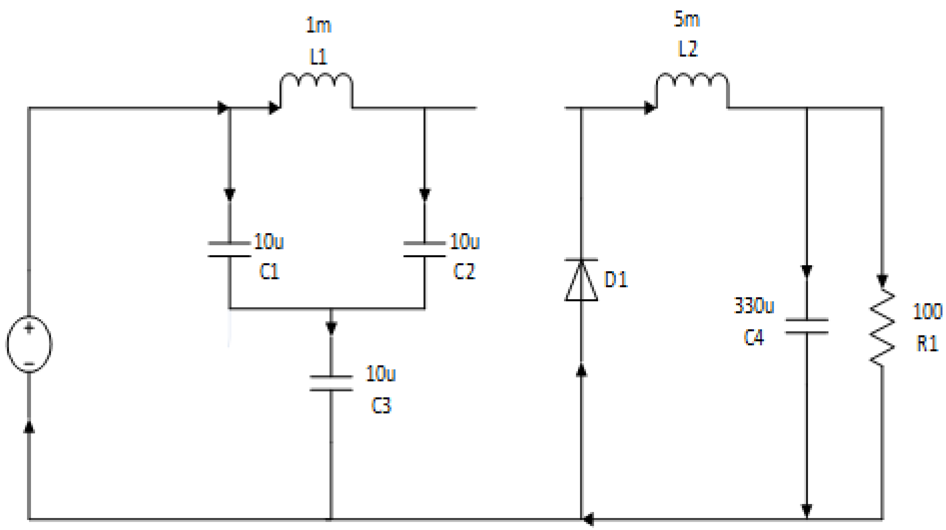
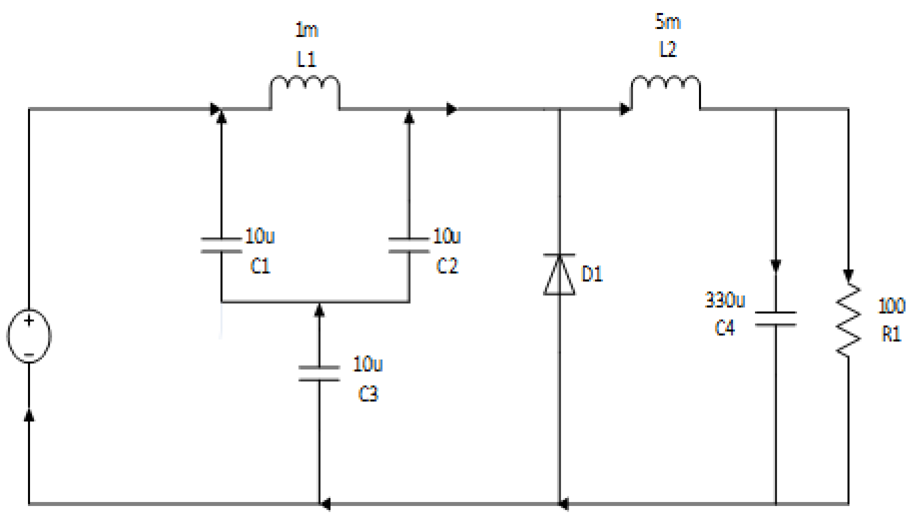


Figure 3

Closed loop topology of the proposed converter



(a)



(b)

Figure 4

(a) Operating principle of the proposed converter (Ton). (b) Operating principle of the proposed converter (Toff).

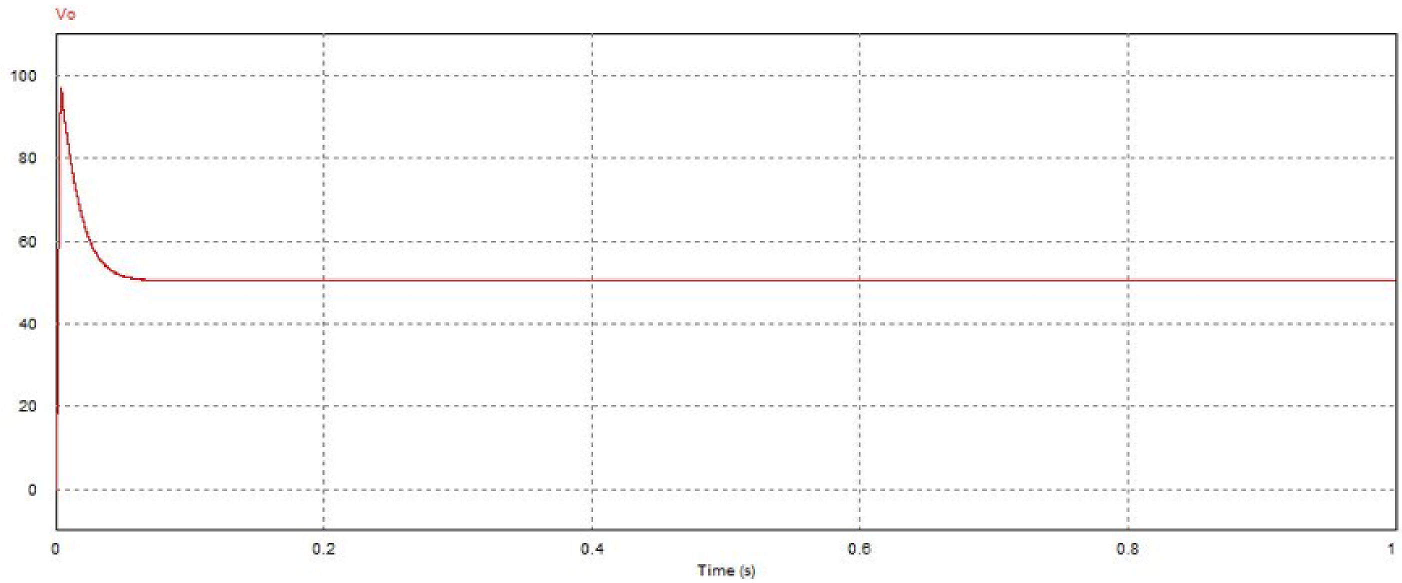


Figure 5

Output voltage of DC-DC topology

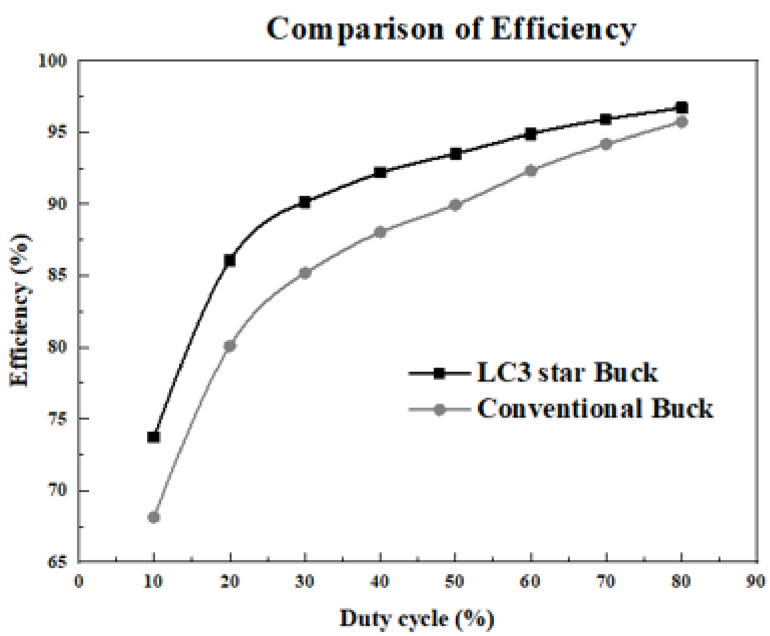


Figure 6

Efficiency comparison of DC-DC topology

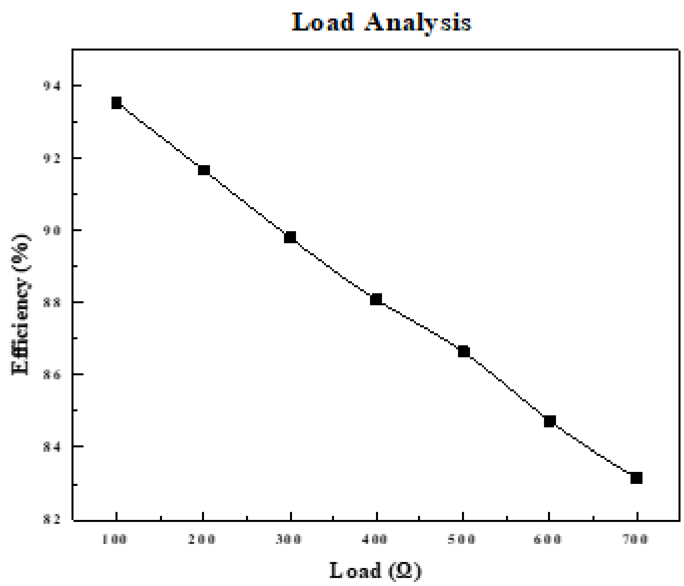


Figure 7

Load Analysis

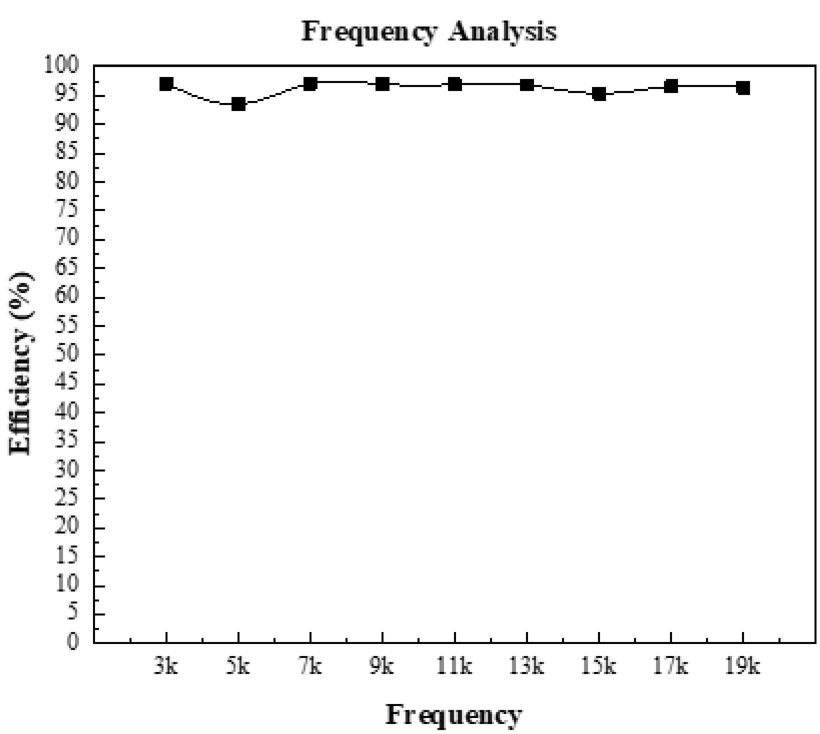


Figure 8

Frequency Analysis

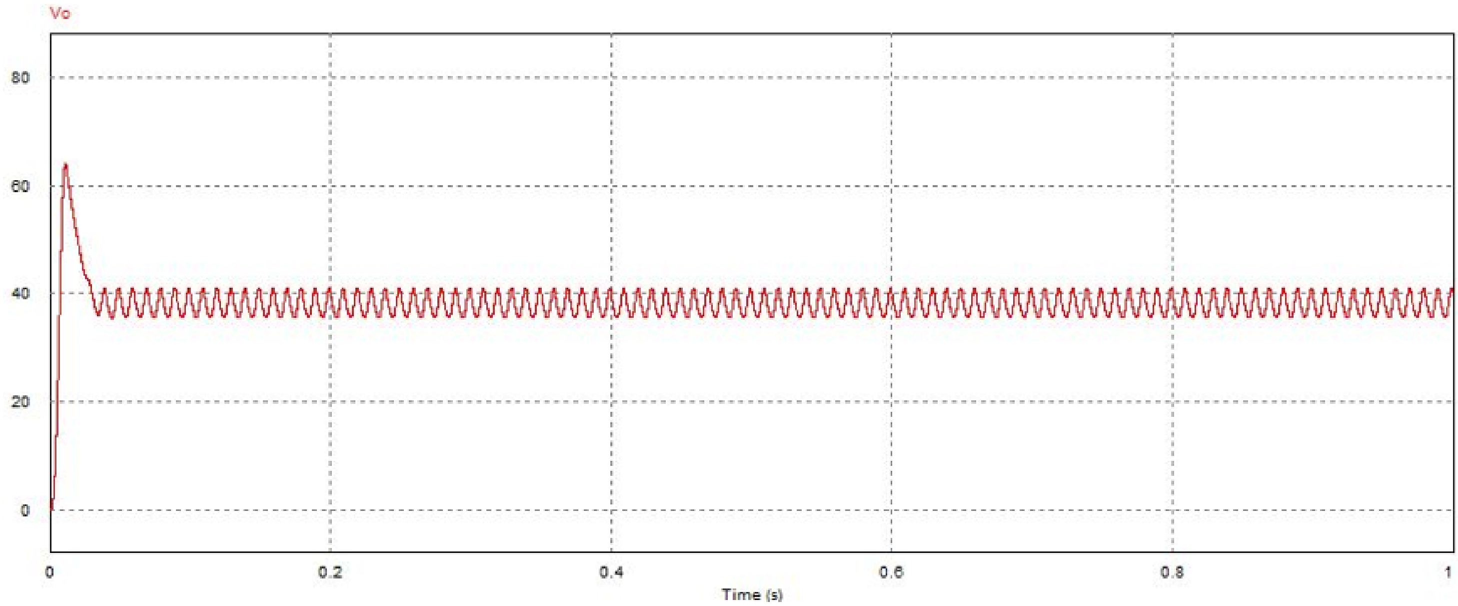


Figure 9

Output voltage of AC-DC topology

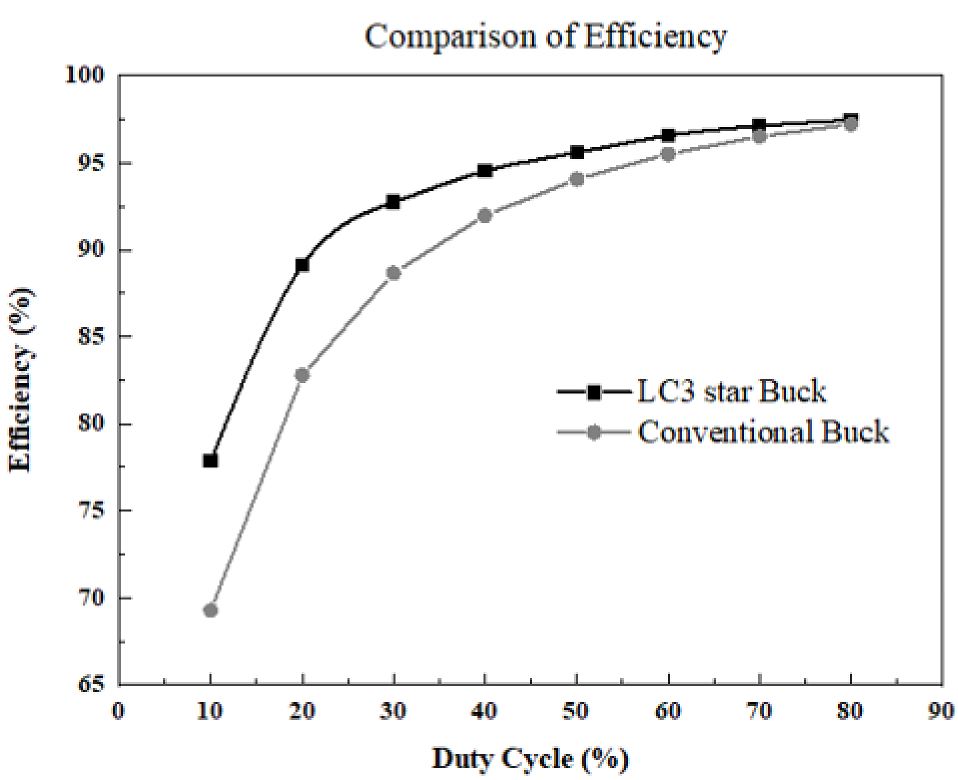


Figure 10

Efficiency comparison of AC-DC topology

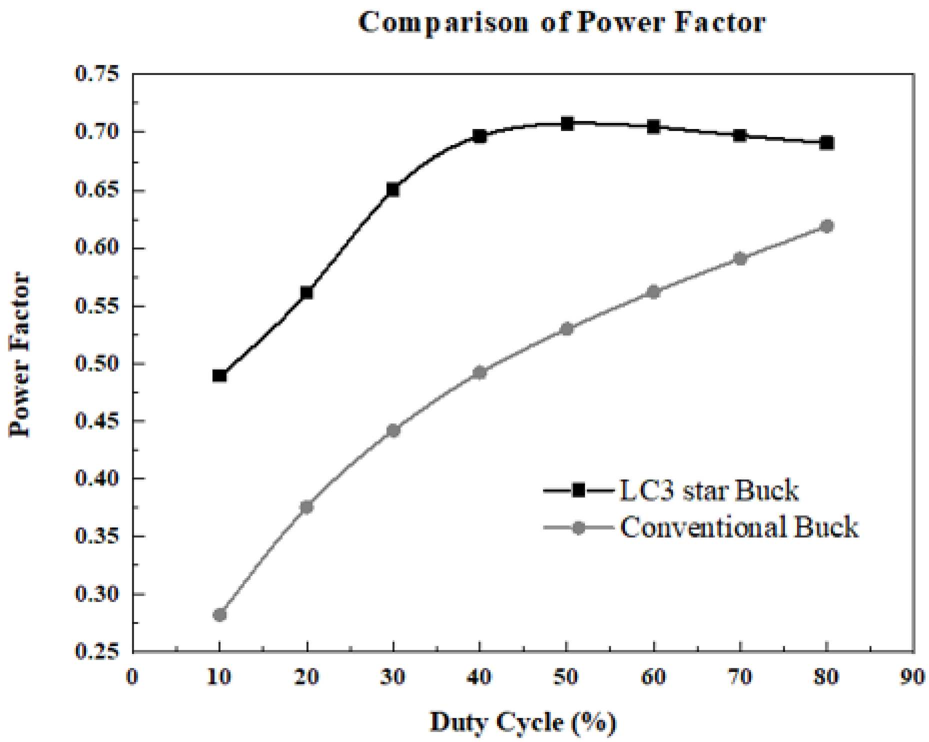


Figure 11

Power factor comparison

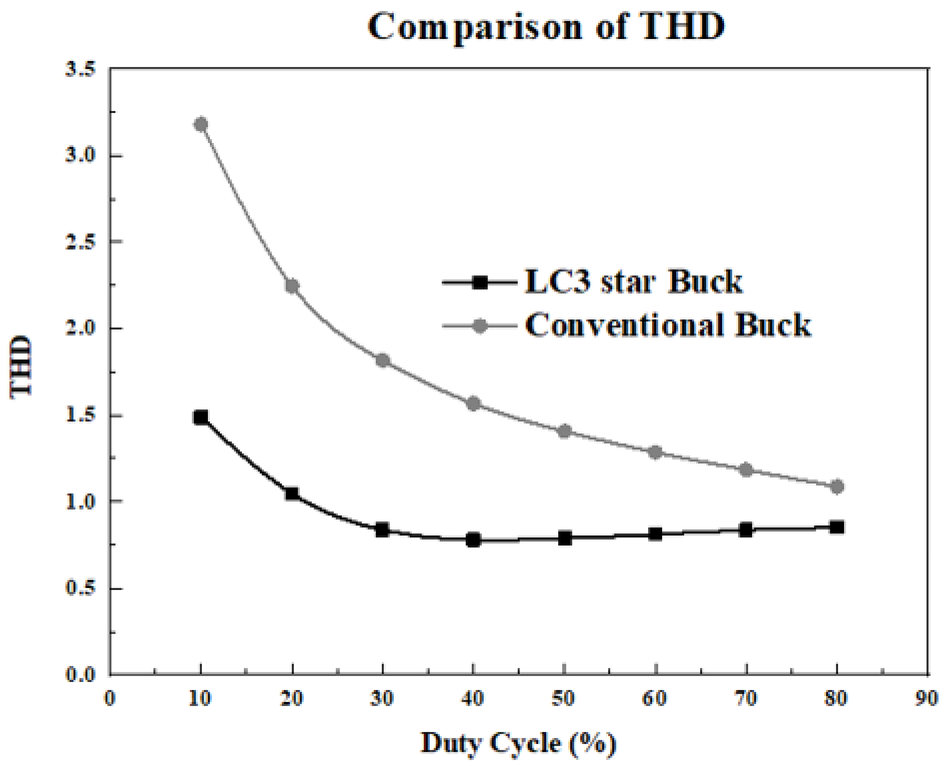


Figure 12

THD comparison

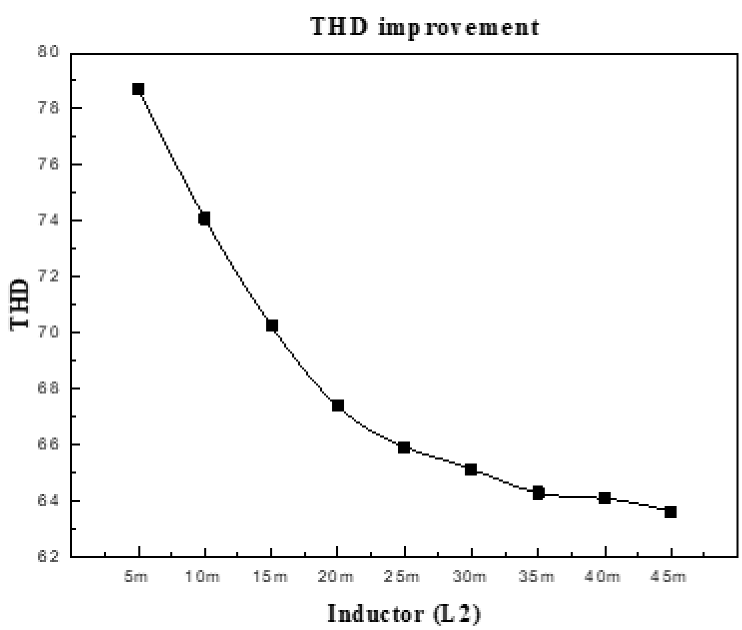


Figure 13

Improvement of THD% with L_2

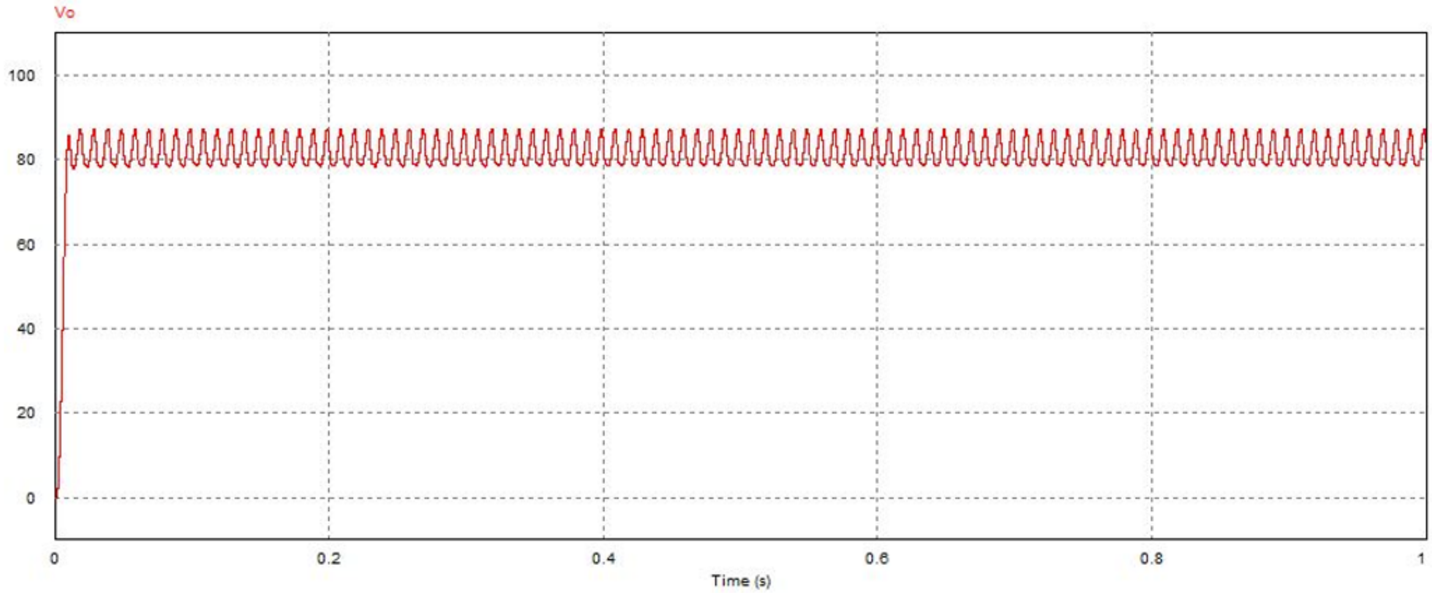


Figure 14

Output voltage of closed topology

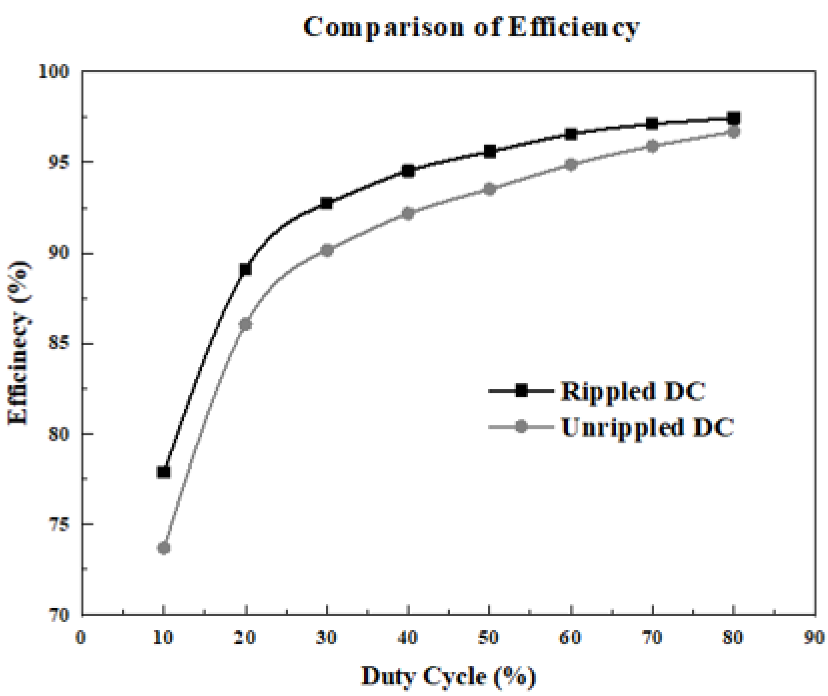
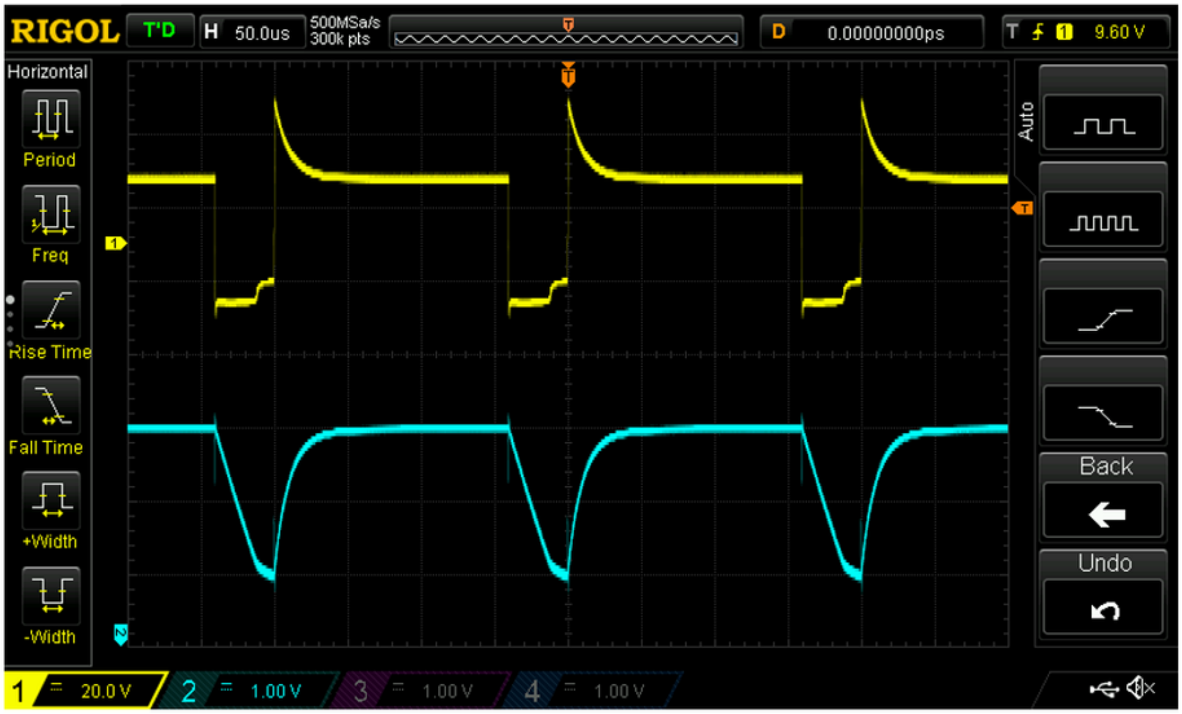
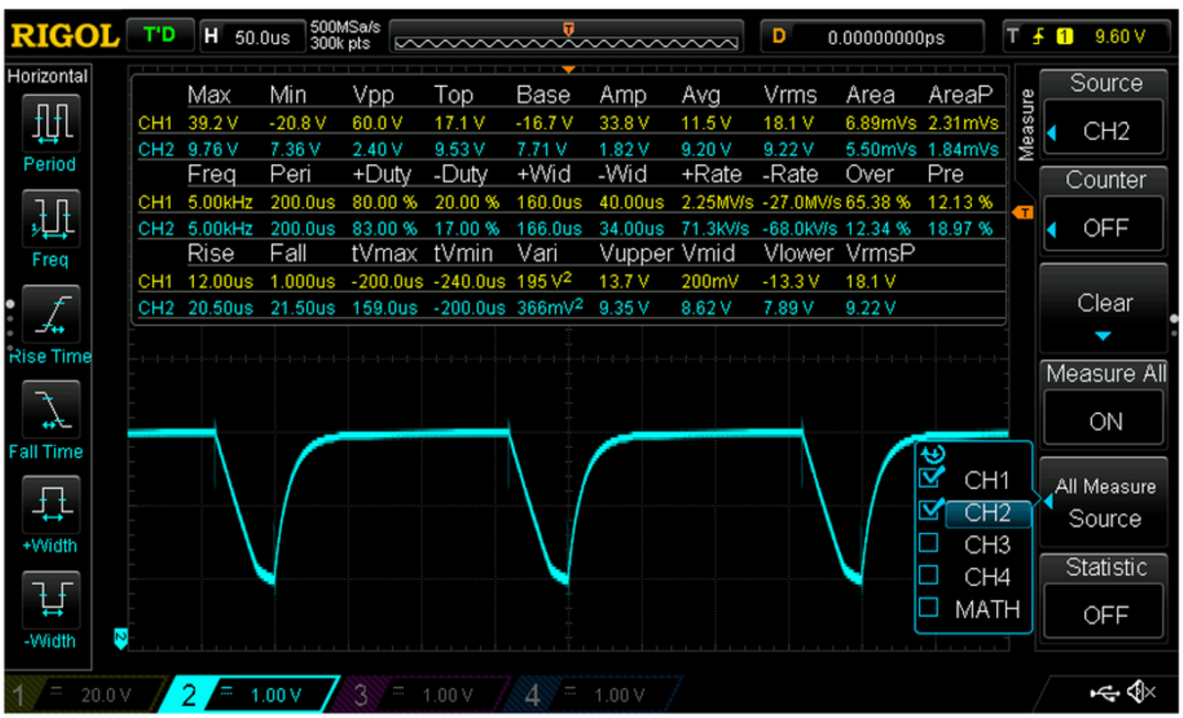


Figure 15

Efficiency comparison between rippled and unrippled source



(a)



(b)

Figure 16

Output voltage from DC-DC prototype