A Dual Inductor High Step-up and Reduced Ripple DC/DC Converter Based On Modified Karthaus-Fischer Voltage Mutiplier

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Abstract- Karthaus-Fischer voltage multiplier is a capacitor-diode voltage multiplier that can be used in applications like photovoltaic, fuel cells and other renewable energy sources. The traditional multipliers commonly used were voltage doubler, Dickson charge pump and Cockcroft-Walton voltage multipliers. Karthaus-Fischer voltage multiplier uses a topology in which the inputs of all voltage multiplying stages are parallel connected whereas their outputs are fed into voltage clamp of next multiplying stage. The dual inductor DC/DC converter based on modified Karthaus-Fischer voltage multiplier leads to high step-up of input voltage with reduced ripple. A comparative study of performance of dual inductor DC/DC converter with Cockcroft-Walton and Karthaus-Fischer voltage multipliers is carried out. The topology is simulated in MATLAB/SIMULINK version 2017a. The hardware is implemented using microcontroller PIC16F77A. The switches are driven along with its driver TLP250.
Keywords– Cockcroft-Walton voltage multiplier,Karthaus Fischer voltage multiplier,dual inductor DC-DC converter

I. INTRODUCTION

Green energy helps to reduce carbon emission from fossil fuel, harvesting energy from natural resources like wind to power consumer appliances. Nowadays many researches have been concentrating on designing circuits that harvest energy from electromagnetic signals wirelessly. It could be designed to be more efficient but the generated power however is insufficient to drive large loads. Wind energy is available environmentally but the development of small-scale energy harvesting apparatus aiming to extract significant power from miniature brushless fan has received limited attention. For the energy harvesting the voltage multipliers contribute to a large extend.

Due to various types of applications, there is always a demand for much higher voltage level. However, based on the energy sources or insulation limits, subsisted power supplies could produce voltages lower than the irrequisite. Therefore, many attempts have been made to discover ways to generate a voltage, higher than the supply voltage. Many methods have been utilized to do this task. Some of the most commonly applied methods for producing a voltage larger than the power supply voltage include step-up transformers, voltage doubler, multiplier circuits, charge pump circuits, switched-capacitor circuits, and boost or step-up converters. Among these methods, diode-capacitor topologies are more suitable.

Cockcroft-Walton Voltage Multiplier is the common capacitor-diode voltage multiplier circuit and it has been widely used in several applications such as telecom equipment, X-ray systems, and laser systems[1]. Recently, employing such voltage multipliers in renewable energy sources are considered because of several advantages like low and uniform stress per stage on diodes and capacitors, wide range of multiplication stages is achieved, compactness, reduced weight, cost efficiency and negative output through reversing diode polarity. John Douglas Cockcroft and Ernest Thomas Sinton Walton developed a voltage multiplier in 1932 for powering their particle accelerator [10]. The circuit proposed is basically cascading stages of Greinacher voltage doubler and thus it is also known as Greinacher voltage multiplier. With the cascading connections described, the output voltage could be further boosted by arbitrary times higher but at the cost of reduction in current drivability. Also, the output impedance increases proportionally with the number of multiplying stages as more stage capacitances are connected in series. Ideally, the n-cascading stage voltage doublers produces 2n times increased in output voltage. In practice, the output voltage of Cockcroft-Walton voltage multiplier drops significantly from ideal prediction especially when the number of multiplying stages increases and significant loading current occurs at output.

Karthaus and Fischer [5] simplified and improved circuit of the Cockcroft-Walton in 2003 [4]. This modified circuit configuration was modifying the Dickson circuit [7] transformation. However, in Karthaus-Fischer cascade voltage-doubler [5], as the numbers of coupling and stray capacitors were reduced, the clock pulses were eliminated. Therefore, the essential requirements of the circuit became less than the Dickson circuit. Based on the achievement, the Karthaus Fischer circuit [5] can be utilized for high-voltage applications. In addition to that, the input impedance of the Cockcroft Walton circuit [4] was reduced by changing the connection of the coupling capacitors, and its output capacitance is increased by using an independent grounded stray capacitor for each stage, in Karthaus-Fischer circuit [5].

The increased use of photovoltaic (PV) panels for solar power in recent years has led to a great deal of research in DC-DC converter topologies suitable for PV applications. Recent advancements in the renewable energy have created a need for both high step-up and high efficiency DC-DC converters. These requirements have typically been addressed with converters using high frequency transformers to achieve the desired gain. The capacitor ladder in Cockcroft Walton multiplier allows for high voltage gains without a transformer. The cascaded structure limits the voltage stresses in the converter stages, even for high gains [5].
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II. PROPOSED CONVERTER

2.1 Circuit Configuration and Operating Modes

High step-up dual inductor DC-DC converter is working on the basis of current-fed two inductor topology and Karthaus-Fischer voltage multiplier which is a diode-capacitor cascaded voltage multiplier. In this converter, the low input voltage will be converted into a high voltage. The dual inductor high step up DC/DC converter consists of two low voltage switches S_1 and S_2. S_1 and S_2 operate in a complementary mode. In an n-stage voltage multiplier, there are N(= 2n) capacitors and diodes. There are four diodes D_1, D_2, D_3, and D_4, two inductors L_1 and L_2, four capacitors C_1, C_2, C_3 and C_4 in a two stage multiplier. V_{in} is the input voltage and output voltage is denoted as V_o.

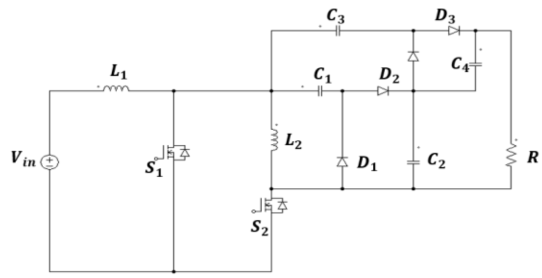


Fig.2. Configuration of the proposed Converter

For analysis of different modes of operation some assumptions are taken. All of the circuit elements are ideal, and there is no power loss in the system. Equal capacitance value is taken for all capacitors and the converter is operating in CCM and in the steady-state condition. When the inductor transfers the storage energy to the Karthaus-Fischer circuit, two of the diodes in the circuit will be conducted. We assume constant voltage at converter output and ignoring safe commutation states (overlap time). According to the state of the switches (ON/OFF), operation of the converter in a switching period (T_s), is divided into two modes that is mode 1 and mode 2. In mode 1 switch S_1 is ON and in the mode 2 the switch S_2 is ON. As in a common diode-capacitor voltage multiplier the voltage get boosted on each stage. The theoretical waveform of mode 1 and mode 2 are shown in figure 5.
Mode 1: (t_0-t_1) [refer figure. 3]: The switches S_1 is ON and S_2 is OFF in Mode 1. The voltage across L_1 is equal to the input voltage (V_{in}); therefore, I_{L1} increases, while L_2 transfers the stored energy to the Karthaus-Fischer circuit. That is L_2 is discharged with respect to the applied voltage. During positive half cycle, diodes is conducted with the sequence D_1, and D_3 and the capacitors are charged (discharged) through the conducting diodes. Similar behaviour occurs during the negative half cycle, while the diodes conducted with the sequence D_2 and D_4 according to that respective capacitors are charged (discharged). t_0 to t_1 is defined as the conduction period for mode 1. Since switch S_1 is ON diodes D_1 and D_2 begins to conduct. Capacitors C_1 and C_3 charges accordingly and the other two capacitors C_2 and C_4 begins to discharge. There will be 4 paths for conduction. Since S_1 is in ON state L_1 begins to charge through Vin. L_2 discharges through the path containing D_1 and C_1. The third path for conduction will be including L_2, C_2, D_3 and capacitor C_3. The fourth path of conduction will be through load resistance R. The two capacitors C_2 and C_4 will discharge through the load resistance R. Figure.3. shows the equivalent circuit diagram of the converter and current paths for this mode is also shown.

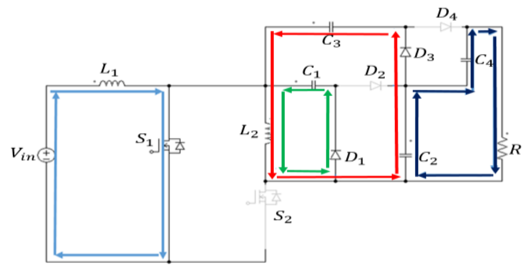


Fig.3. Mode 1 Operation

Mode 2: (t_1-t_2) [refer figure. 4]: The switches S_2 is ON and S_1 is OFF in Mode 1. This state will lasts for DT_s (D is the duty cycle) to T. The voltage across L_1 is which was charging in mode 1 now begins to discharge; therefore, I_{L1} decreases, while L_2 store energy. That is L_1 is discharged with respect to the applied voltage. During the negative half cycle, while the diodes conducted with the sequence D_2 and D_4 according to that respective capacitors are charged (discharged). Since switch S_2 is ON diodes D_2 and D_4 begins to conduct. Capacitors C_2 and C_4 charges accordingly and the other two capacitors C_1 and C_3 begins to discharge. There will be 3 paths for conduction. Since S_1 is in OFF state L_1 begins to discharge through V_{in} and L_2. L_2 charges through the path containing D_2, C_1 and C_2. The third path for conduction will be including L_2, C_2, D_4, C_4 and capacitor C_3. Figure 4 shows the equivalent circuit diagram of the converter and current paths for this mode is also shown.

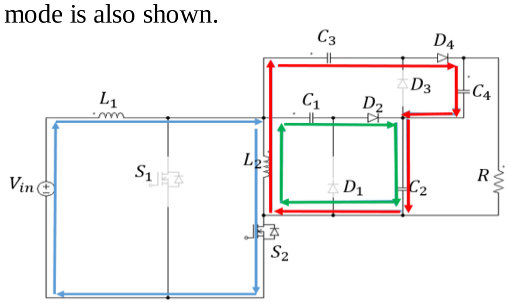


Fig.4. Mode 2 Operation

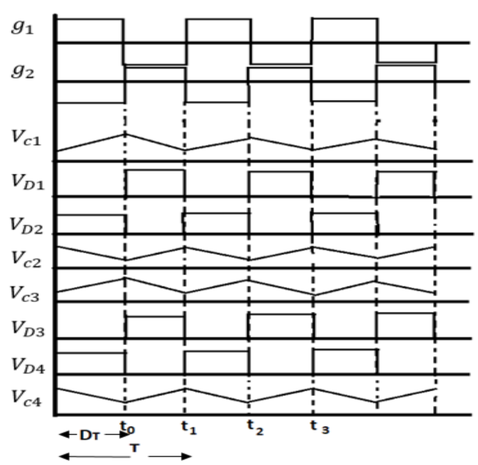


Fig.5. Theoretical Waveforms of Proposed Converter

2.2. Design Considerations

The input voltage is taken as 24 V. The pulses are switched at the rate of 100 kHz with a duty ratio of 0.35. The design is done so as to get an output power of 200 W. Since it is a 2 stage voltage multiplier the n is taken as 2. In order to design a power electronic converter, voltage and current stresses taken as minimum values for inductors and capacitors.

In order to study the steady-state behaviour of the proposed converter, a number hypotheses are assumed. They are Continuous Conduction Mode (CCM) operation, ideal elements for converter, constant voltage at converter output, equal capacitance value of all capacitors and ignoring safe commutation states (overlap time).

1. Inductance

The value of L_1 is determined according to maximum allowed input current ripple (ΔI_{L1}). On considering the worst condition

$$L_1 = \frac{D^2(1-D)\cdot V_{out}}{n\cdot f_s \Delta I_{L1(\min)}} \xrightarrow{D_{\max}=0.7} L_1 = \frac{0.15\cdot V_{out}}{n\cdot f_s \Delta I_{L1(\min)}} \qquad (1)$$

Minimum value of L_2 are determined by

$$L_2 = \frac{D_{\max}(1-D_{\max})^2 R}{2n^2 f_s} \xrightarrow{D_{\max}=0.35} L_2 = \frac{0.15R}{2n^2 f_s} \qquad (2)$$

2. Capacitance of CW-VM

The value of capacitors in the CW-VM is determined by the desired output voltage ripple. In order to increase the dc gain by increasing n, the number of diodes in the CW multiplier will increase, and thus the conduction losses of diodes. This may result in decreasing overall efficiency. Therefore, to find the appropriate number of n, tradeoff between power loss of diodes and MOSFET should be done.

3. Number of Stages

As the number of stages increased, in order to increase the DC voltage gain, conduction losses increases. As the lower number of n, voltage stress on the MOSFET increases. Therefore, to find an appropriate number of n, tradeoff between power loss of diodes and MOSFET should be done.

III. SIMULATION OF PROPOSED CONVERTER WITH RESULTS

Simulation parameters for the high step up DC/DC converter is given in Table 1. An input voltage V_{in} of 24 V gives an output voltage Vo of 311 V for an output power P_o of 200 W. The switches are MOSFET/Diode with constant switching frequency of 100 kHz. The duty cycle of switches is taken as D=0.35.

Table.1. simulation parameters

Parameters	**Specification**
Input voltage V_{in}	24V
Switching frequency f_s	100kHz
Output voltage V_{out}	311V
Inductor L_1 L_2	100µH 50µH
Output power P_o	200W
Capacitor	220µF
Load Resistance R_o	500Ω

a.

The Karthaus-Fischer converter is simulated in MATLAB/SIMULINK by choosing the parameters listed in Table 1 and the Simulink model is shown in figure.6.

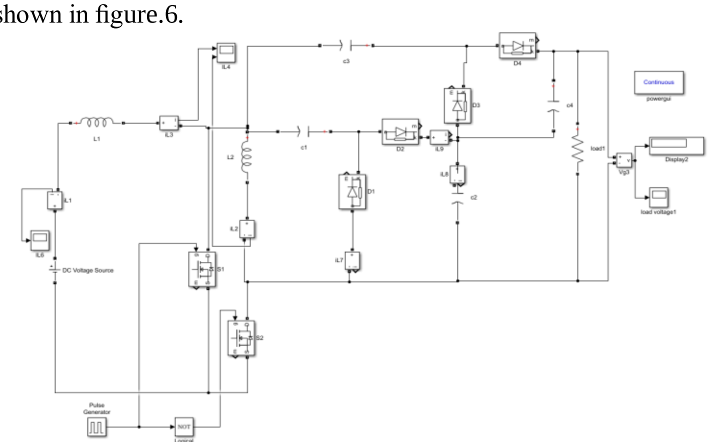


Fig.6. Simulink Model of Proposed Converter

Figure.7. shows the switching pulses and switching voltage across S_1 and S_2. The switching frequency is chosen to be 100 kHz and the duty ratios of S_1 and S_2 is equal to 0.35. The voltage stress V_{S1} and V_{S2} are 69 V and 65 V respectively. Even though the output voltage is very high the resultant stress on the two switches in the converter is low.

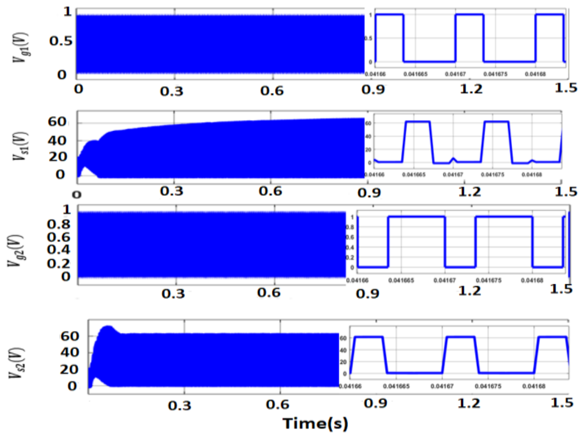


Fig.7. (a) S_1 Gate Pulse, (b) S_1 Gate Voltage, (c) S_2 Gate Pulse
(d) S_2 Gate Voltage

It is shown in figure.8. The input voltage into the Karthaus-Fischer converter is 24 V and the resulting input current in the input is 6.7 A.m. The ripple in the input current is about 1.8 A.

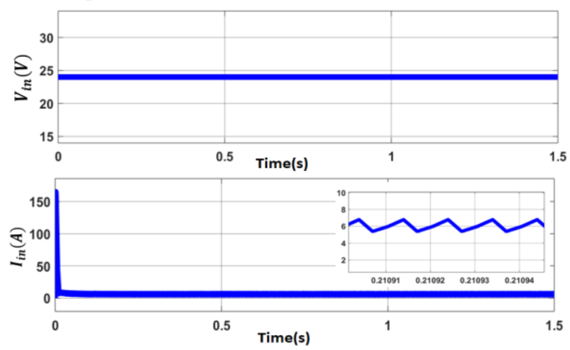


Fig.8. (a) Input Voltage (V_{in}) and (b) Input Current (I_{in})

Since I_{in} is equal to current through inductor L_1, the I_{L1} will be equal to 6.7 A. From the figure.8. It can be seen that the current through L_2 is 6.3 A. In case of L_2 ripple in the current is about 1 A.

From fig.9. It can be seen that the output voltage Vo is 310 V with I_{out} of .5 A. By using output voltage, current, input voltage and current the calculated efficiency will be very high as much as 94.2%. The ripple in the output voltage is about .0002V. This verifies the high step up voltage gain and also from the figure figure.9 (a) it is evident that the output ripple voltage is very low as .02%.

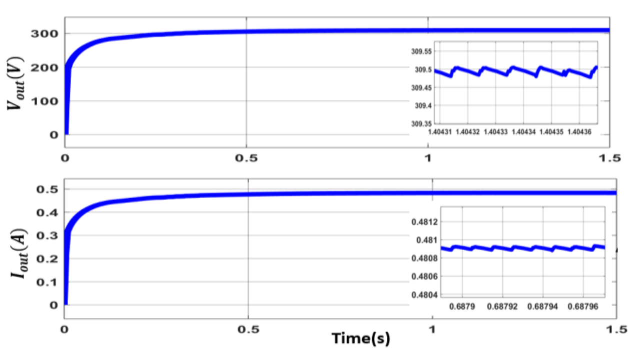


Fig.9. (a) Output Voltage(V_{out}), (b) Output Current(I_{out})

IV. ANALYSIS

The analysis of Karthaus-Fischer voltage multiplier based converter is carried out by considering parameters like voltage gain, efficiency, voltage stress, input power, output power and duty ratio etc.

1. Efficiency Vs Output Power for R Load and R-L Load

Efficiency of the power equipment is defined at any load as the ratio of the power output to the power input. The efficiency gives us the fraction of the input power delivered to the load. A typical curve for the variation of efficiency as a function of output power for R load and R-L load is shown in fig.10. The converter efficiency is around 94.2% for 200W output power for R load and for R-L load the efficiency is about 92%.

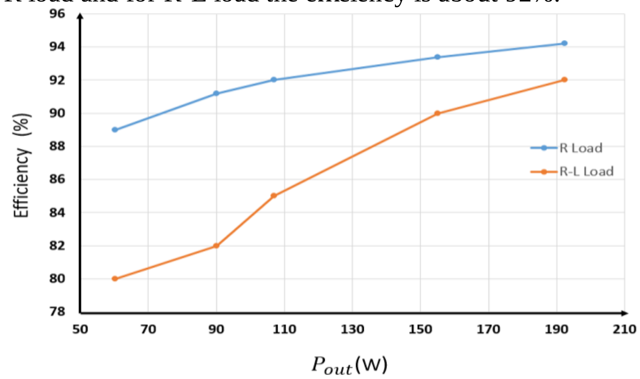


Fig.10. Efficiency Vs Output Power

2. Voltage gain Vs Output power

The plot of voltage gain as a function of output power is shown in figure 11. According to figure, it can be observed that, up to 192.2 watt, voltage gain is more than 10 that is about 12.9. In a CW-VM converter as the number of voltage multiplying stages, the voltage gain also increases

3. Efficiency Vs Input voltage

The plot of efficiency Vs input voltage is shown in fig.12. In fig.12. illustrates that the efficiency is rather constant while the input voltage of converter varies. For a voltage of 12 V, the efficiency is about 89.5%. Also for the voltage of 24 V the efficiency is 94.2%. So as a conclusion, for the variation of 12 V to 24 V the efficiency remain in between 90-93. The property of having constant output power for a wide range of input voltage has main application in PV and fuel cells where the input voltage continuously varies. So by the application of dual inductor Karthaus-Fischer converter even if for input variation, the efficiency remain higher.

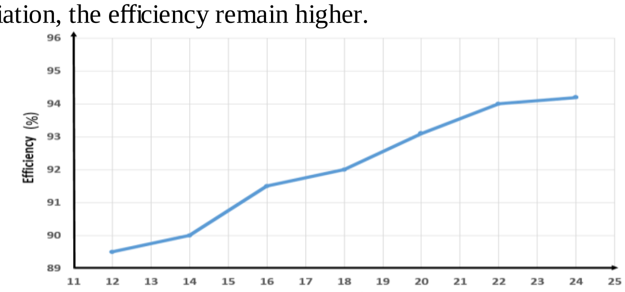


Fig.12. Efficiency Vs Input Voltage

4. Power Loss Distribution

According to the non idealities of Karthaus-Fischer multiplier based converter, the main power losses occur in L_1, L_2, S_1, S_2 and diodes. The power losses of each components of Cockcroft Walton multiplier and Karthaus-Fischer based converters are shown in figure.13. The conduction loss of inductor L_1 is 0.4 W and the conduction loss of inductor L_2 is 0.46 W. The power losses of switches are 0.55 W. The conduction losses of capacitor is very less. It is only about 0.16 W. On comparing with other component's losses, the conduction loss of diode is a little higher, that is about 1.3 W.

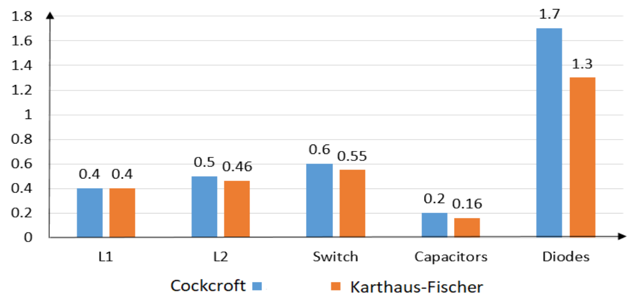


Fig.13. Power Loss Distribution

V. COMPARISON

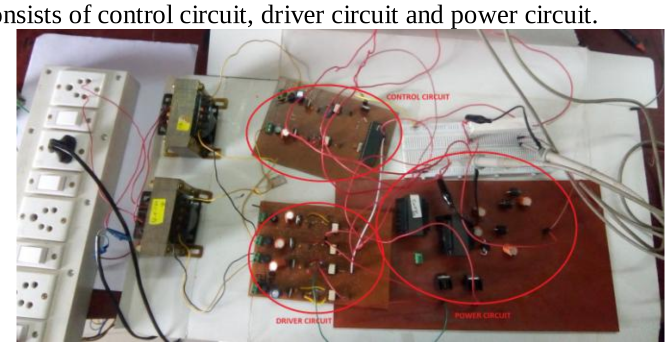
In order to evaluate the CW-VM converter, five structure, with similar applications are taken into consideration. The converters are dual inductor Cockcroft-Walton multiplier based converter, switched capacitor boost (SC-Boost), switched inductor (SL-Boost), switched capacitor cuk (SC-Cuk), and switched inductor SEPIC (SL-SEPIC). The criteria considered for the comparison are voltage gain, number of semiconductor devices and voltage stress on switches and common ground.

Table.2. comparison

	Dual inductor CW-VM converter	SC-boost	SL-boost	SC-cuk	SL-SEPIC	Modified Converter
Common ground	No	No	Yes	No	Yes	yes
No.of switch	2	1	1	1	1	2
No.of diode	6	2	4	2	2	4
Voltage gain	12	2.07	2.07	2.07	.72	12.91
V_s	S_1=68v	49.84	49.84	49.84	23.55	S_1=65V
	S_2 =62v					S_2 = 60v
output voltage ripple	0.09	—	—	—	—	0.0002

It is observed from the above discussions that in the modified Karthaus-Fischer DC-DC converter ,the voltage stresses on the switches are reduced and output voltage ripple is also reduced.

A prototype of modified Karthaus-Fischer DC/DC converter is implemented. The topview of the experimental setup is shown in figure.14. It consists of control circuit, driver circuit and power circuit.



VI. CONCLUSION

A dual inductor high step up DC/DC Karthaus-Fischer voltage multiplier based converter offer low ripple output voltage and high efficiency. The current-fed converter eliminates some problems associated with the conventional voltage-fed type such as voltage ripple and load-dependent voltage droop. The other advantages are compactness, low weight and cost efficiency. It utilises a current fed high step up DC-DC converter topology without utilizing extreme values of duty cycle or boosting transformers. It also provides continuous input current and high voltage gain. For the converter, the voltage gain is about 12.9. The input voltage is 24 V and output voltage is 310 V, this verifies the high step-up voltage gain. The converter has an efficiency of 94.2% with a duty cycle of 35% . This converter can be used for applications with high input voltage and low output voltage such as battery chargers, distributed power systems, solar panels etc.

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