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The Derivative of a Switched Coupled Inductor DC–DC Step-Up Converter by Using a Voltage Lift Network with Closed Loop Control for Micro Source Applications

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Abstract: ***The derivative of a switched coupled inductor DC-DC step-up converter by using voltage lift network for micro source application is handling in this paper. High voltage gain is obtained by employing a switched coupled inductor and a switched capacitor in to one converter. The coupled inductor charges the capacitor, the voltage gain can be effectively increased, and the turns ratio of the coupled inductor can be also reduced. The output and the voltage conversion ratio of this converter can be enlarged by adding a voltage lift network. A module with capacitor and diode will form the voltage lift network. In this derivative circuit, capacitors are charged in parallel during the switch-on period and are discharged in series during the switch-off period. Beside from high voltage gain, lower conduction loss and higher power conversion efficiency is also offered as compared to conventional dc-dc converter. The steady state analysis and operating principles in continuous conduction mode are discussed. To study the performance of the switched coupled inductor high step up DC-DC converter with voltage lift network, simulations has been carried out in MATLAB 2013 environment. The derivative circuit design and its implementation with closed loop control are given with operational results. The simulation results are tested for an input voltage of 20V. The input voltage is stepped up to output voltage of 220V, while by adding voltage lift network output voltage is lifted to 325V, which can be used for various applications.***

Keywords: coupled inductor, high step-up converter, switched capacitor, voltage lift network

1. Introduction

Nowadays renewable energy sources are widely used in distributed generation (DG) systems. DG systems are composed of micro sources like fuel cells, photovoltaic (PV) cells, wind power etc. However fuel cells and photovoltaic cells are low voltage sources to provide enough dc voltage for generating ac utility voltage. PV cells can be connected in series in order to obtain a large output voltage. But the main drawback is the efficiency is degraded due to the panel mismatch and partial shadowing. The PV panel parallel connected structure is more efficient than the series-connected configuration. Meanwhile, only a low voltage is generated with parallel connected Configuration. So, high step up converters are used as a solution for the aforementioned problem. These converters boost the low input voltage into high voltage level. However these converters are used in many other applications, such as portable fuel cell systems, and vehicle inverters where high efficiency, high power density, and low cost are required.

The conventional STEP-UP dc-dc converter is easy to control and its structure is very simple. But in this case, this converter will be operated at extremely high duty ratio near unity, to achieve high step-up voltage gain [2], [6]. This will cause high conduction loss due to the reverse recovery problems of output diode and large input current. However, the voltage gain and the efficiency are limited.

Isolated converters can achieve high voltage gain without operating at extreme duty ratio. But the voltage stress across the switch is higher, and the efficiency is also reduced. So an active clamp technique can be introduced to improve the efficiency. But this will increase the number of components used, moreover the weight and size of the converter is higher which reduce the power density.

DC–DC converters with coupled inductors can provide high voltage gain. A coupled inductor basically consists of two identical windings wound onto one core. The important criterion is that the windings are exactly identical to generate the coupling effect. From an economical standpoint, the use of coupled inductors saves cost and reduces the size. It also helps to save actual PCB real estate, due to the usage of one component with 2 integrated windings. From a technical standpoint the advantages of a coupled inductor are as follows:

If L1 and L2 are closely coupled, the ripple current is divided between them, and the required inductance is halved. In some applications, there is even close to zero ripple current due to the use of a coupled inductor. This also results in a simpler EMI filtering and smaller input capacitor. But their efficiency is degraded by the losses associated with leakage inductors. The leakage inductance of the coupled-inductor will cause a high voltage spike on active switches when the switches were turned off [17]. Alternatively, employing an active clamp technique to recycle the leakage energy can achieve soft switching for active switches [10]. The active-clamp flyback converter can recover the leakage energy and minimize the voltage stress. The drawbacks of the active-clamp solution are the topology complexity and the loss related to the clamp circuit. The active-clamp solution requires two switches and two isolated gate drivers. The current through the

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active clamp switch is the high primary current, which can induce high conduction losses in the active-clamp circuit.

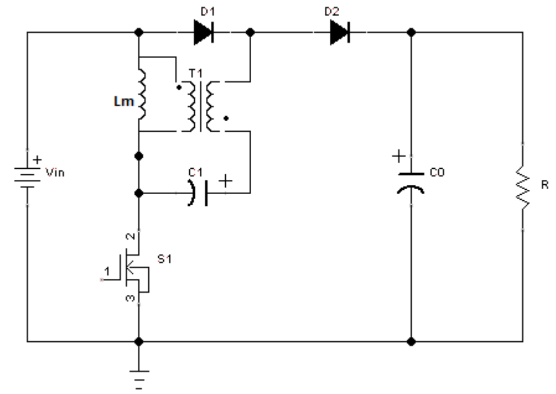


Figure 1: Earliest proposed scheme

A high step-up dc-dc converter with coupled inductor shown in figure 1.This converter can provide a high voltage gain than the conventional dc-dc converter. Besides from high voltage gains, lower conduction loss and higher power conversion efficiency is also offered as compared to conventional dc-dc converter. Meanwhile, because of the effect of parasitic elements, the power transfer efficiency and output voltage is restricted. Voltage lift technique is a popular method widely used in electronic circuit design.

Hence here proposing a new topology, a switched coupled inductor DC-DC step up converter by adding a voltage lift network with voltage mode control is simulated in the environment of MATLAB. The main advantage of using voltage lift technique is, in order to enlarge the output voltage for particular application, adding a voltage lift network instead of redesigning the whole converter. Voltage lift technique opens a good way to improve the circuit characteristics.

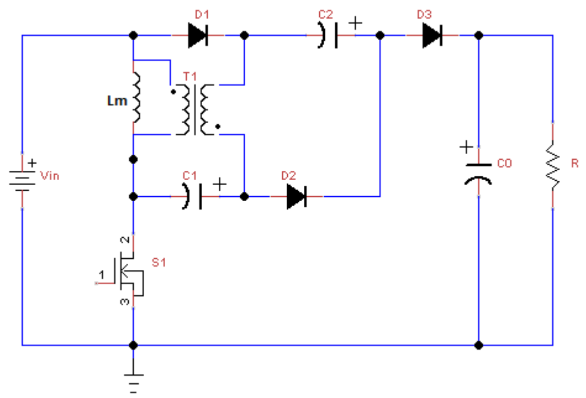


Figure 2: switched coupled inductor high step-up DC-DC converter with voltage lift network

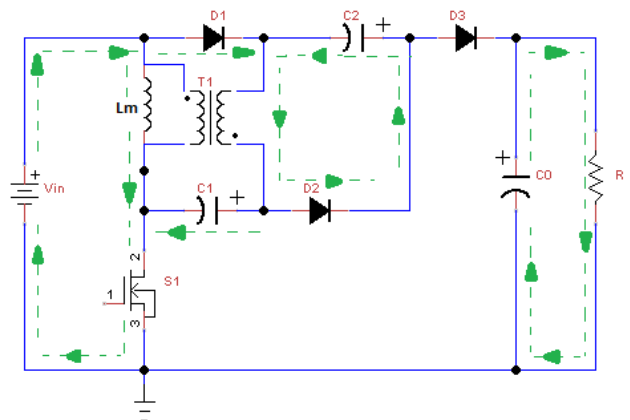
2. Switched Coupled Inductor High Step Up DC-DC Converter with Voltage Lift Network

A high step-up dc-dc converter with coupled inductor is easy to control and its structure is very simple. But because of the effect of parasitic elements, the power transfer efficiency and output voltage is restricted. So the derivative of a switched coupled inductor DC-DC step-up converter by using voltage lift network is discussed in this paper. The voltage conversion ratio can be enlarged by adding a voltage lift network at the output. A module with a capacitor and diode forms the voltage lift network. Voltage lift technique opens a good way to improve the circuit characteristics. This converter provides a voltage gain of 16 times the input voltage with a low duty ratio and turns ratio.

Converter with voltage lift network has several features. That are, increasing conversion with high power density, high efficiency, cheap topology in simple structure. They possess many advantages including the high output voltage with small ripples. Therefore, these converters can be widely used in industrial applications, especially for high output voltage projects. The operating principles and steady state analysis of continuous conduction mode is described as follows.

MODE1: During the time interval DT_s, switch S_1 is on. Thus the diodes D_1 and D_2 is conducting and D_3 is turned off. The current flow path is shown in figure 3 (a). The low voltage side (Vin) energy is transferred to the primary and secondary of the coupled inductor, and to the capacitor C_1. During this mode, switched capacitor C_1 receives energy from the input source and coupled inductor T_1 and capacitor C_2 receives energy from the secondary of coupled inductor. This mode ends when the switch is turned off.

MODE2: Active switch S_1 and diodes D_1 and D_2 are turned off, but diode D_3 is conducting. The current flow path is shown in figure 3 (b). During this mode, energy is being released through the series-connected path that consists of input source Vin, magnetizing inductor Lm, switched capacitor C1, secondary winding N2, capacitor C_2 and diode D2 to charge capacitor C0 and load R. This mode ends when switch S1 is turned on at the beginning of the next switching period.



(a)

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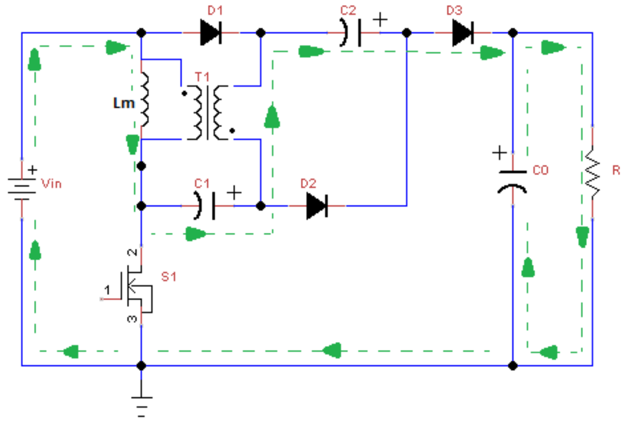


(b)

Figure 3: Current flow path of the switched coupled inductor step up DC-DC converter with voltage lift network (a) Mode 1 (b) Mode 2

The steady-state analysis only takes the CCM operation into consideration, and the leakage inductances at the primary and secondary sides are neglected. The following assumptions are made for the analysis.

1. All components are ideal.
2. Turns ratio of the coupled inductor winding, $n = N_2/N_1$.
3. Capacitors are sufficiently large, voltages on them are considered constant.
4. Magnetizing inductance integrated into primary winding.

Applying a volt-second balance on the primary winding N1 of the coupled inductor yields

$$V_{N1} = \frac{D}{1-D} V_{in} \quad (1)$$

The voltage VN2 of secondarywindingN2 is n times of VN1, i.e.,

$$V_{N2} = \frac{nD}{1-D} V_{in} \quad (2)$$

The output voltage will be the sum of input source Vin, the voltage on switched capacitor C1 and C_2 and the primary and secondary voltages of the coupled inductor. The voltage conversion ratio of the CCM is derived as follows:

$$V_o = V_{in}\left(1 + \frac{D}{1-D} + (1+n) + \frac{nD}{1-D} + n\right) \quad (3)$$

$$G_{CCM} = V_0/V_{in} = \frac{(1+n)(2-D)}{1-D} \quad (4)$$

3. Design of the Proposed Converter

The design of the proposed converter is done at a power level of 250W aiming at high power applications such as distributed generation system. The input voltage here is given by a DC voltage source. The required output voltage is 325V. Various parameters of the converter has been designed accordingly. The specification of the proposed converter is given in table I.

Table 1: Specification of the derivative converter

Parameter	*Specification*
Input voltage, V_{in}	20V
Output voltage, V_o	325V
Rated output power, P_o	250W
Switching frequency, f_s	50KHz

The current through the primary winding of the coupled inductor is same as the input current. So the equation for the current ripple is become,

$$\Delta I_{L1} = V_{in}.D.T_s/L_m \quad (5)$$

In order to calculate the voltage ripple of a capacitor, the following equation is used:

$$V_C(t) = V_C(t_0) + \int_{t_0}^{t} i(t)\,dt \quad (6)$$

Since the average currents through capacitors C_1, C_2 and C_O are zero under steady state, the average current values of diodes are equal to I_O. Therefore, according to the CCM operation, the voltage ripple of all capacitors can be given as follows:

$$\Delta V_{C1,2} = V_o D/R_L f_s C_{1,2}\ ;\ \Delta V_{Co} = V_o D/R_L f_s C_o \quad (7)$$

The voltage lift technique chosen here is the easiest one. So the design of the switched coupled inductor DC-DC step up converter is much simplified. The input voltage ranges between 16V to 24V. The output voltage is regulated at 325V. A higher switching frequency of 50 kHz is also chosen.

Thus the values of the different parameters required for the proposed switched coupled inductor DC-DC step up converter were calculated and found out through the above said equations. The design data obtained for the switched coupled inductor DC-DC step up converter with voltage lift network is given in table II.

4. Simulation Results

In order to verify the performance of the proposed converter, a 20/325V prototype circuit is built in the MATLAB. The simulation parameters are: input voltage Vi = 20 V; output voltage Vo = 325 V; load: resistance load R = 422.5Ω; magnetizing inductance: Lm = 23μH; capacitance: C1 =100 μF, C2 =100 μF; filter capacitor: C_0 = 10 μF; and switching frequency: fs = 50 kHz. Figure 4 shows the Simulink model of the switched coupled inductor high step-up converter with voltage lift network. This converter at this duty ratio gives more than 16 times the input voltage as output voltage (V_{in}=20V and V_o= 325V). The resulting waveforms shown in figure 5 are the switching signal Vgs, voltage and current across the switch vs1, is 1, diode currents iD1, iD2, voltage across the diodes VD1, VD2, voltage across the capacitors V_{C1}, V_{C2} and the output voltage v_0 respectively.

Table 2: Design details developed for the converter

Input voltage, V_{in}	20V
Output voltage, V_o	325V
Rated output power, P_o	250W
Switching frequency, f_s	50KHz
Turns ratio of T_1, n	3
Magnetizing inductance, L_m	23μH
Capacitance of C_1	100μF
Capacitance of C_2	100μF
Capacitance of C_0	10μF

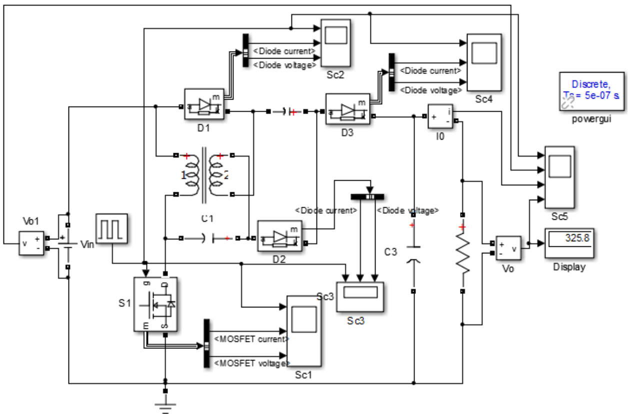
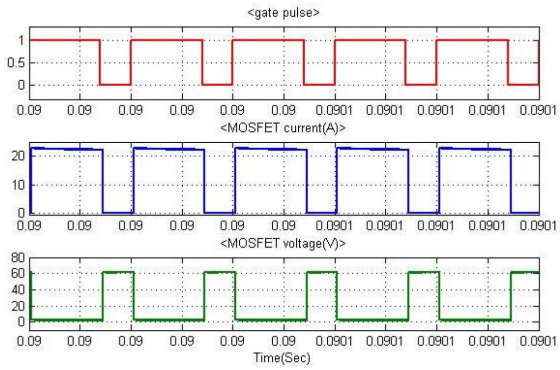


Figure 4: MATLAB Simulink model of the switched coupled inductor high step-up converter with voltage lift network



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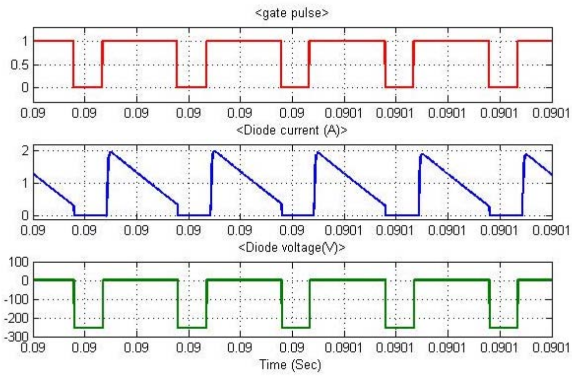

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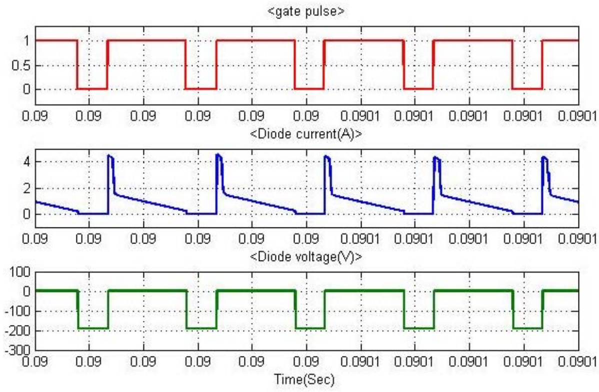

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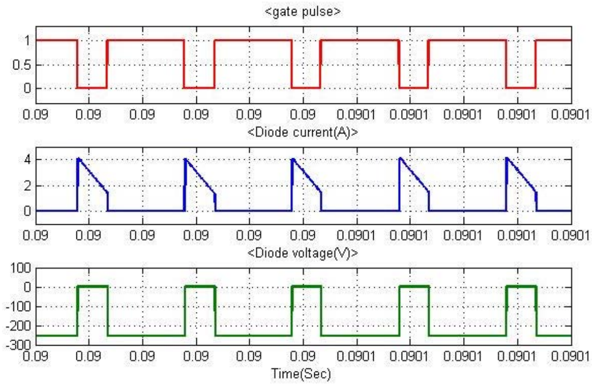

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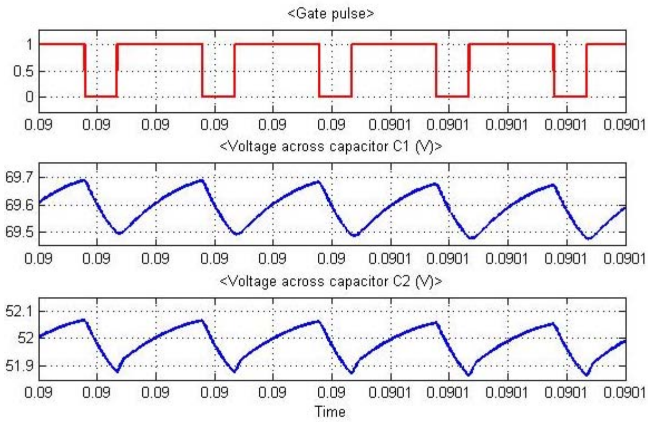

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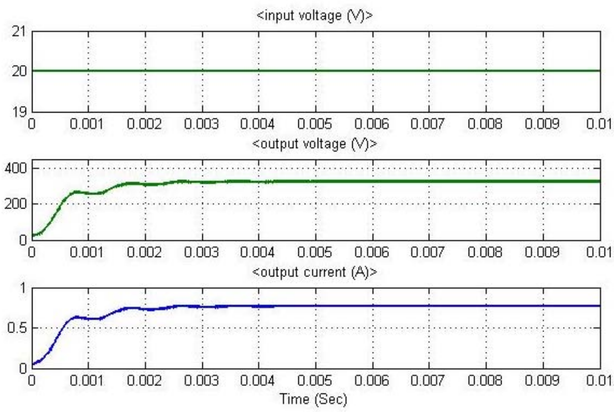


(f)

Figure 5: Simulation results (voltage and current waveforms) of the switched coupled inductor high step-up

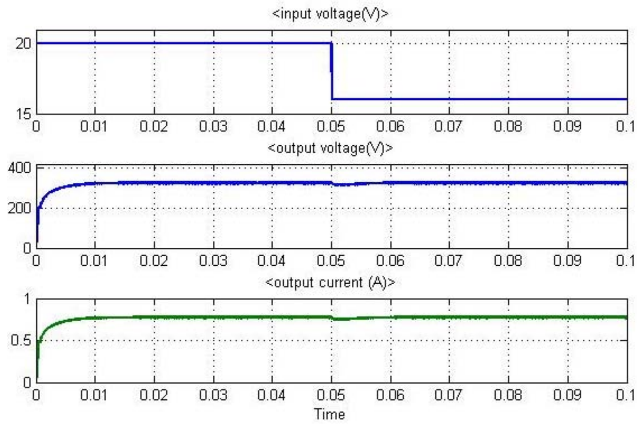
converter. (a) V_{GS}, I_{S1} and V_{S1}, (b) V_{GS}, I_{D1} and V_{D1}, (c) V_{GS}, I_{D2} and V_{D2}, (c) V_{GS}, I_{D3} and V_{D3}, (e) V_{GS}, V_{c1} and V_{c2}, (f) V_{IN}, V_O and I_O

From the simulation results, figure 5 (a) shows the gate pulses, current through the switch during on state and voltage drop across the switch during off state. Here the drain to source voltage of both the MOSFETs is around 60V.The drain current is 20A. The diode D_3 is conducting during off time period of the switch, at this time diodes D_1 and D_2 are non-conducting state, thus a negative voltage drop is there across the diodes, shown in figure 5 (b) and figure 5 (c). The diodes D_1 and D_2 are conducting during on time period, but diode D_3 is off, thus there is a negative voltage drop across the diode D_3, shown in figure 5 (d). Figure 5 (e) shows the switching pulses and voltage across the capacitors C_1 and C_2 respectively. During ON time of the switch, capacitors starts charging and when the switch is turned off, energy stored in the capacitors is discharged to the load. Figure 5 (f) shows the input and output voltages and the output current of the circuit. From the waveforms it is understood that, the output voltage is boosted into 16 times that of the input. That is when input voltage is given as 20V, the output voltage is boosted to 325V. Output current is 0.769 A. The rated load resistor value is 422.5 Ohms.

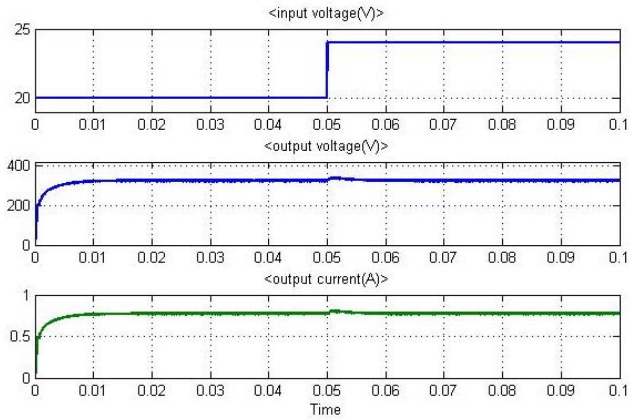
5. Closed Loop Control

The closed loop control of the switched coupled inductor DC-DC step-up converter with voltage lift network has been simulated in order to obtain the voltage regulation. The output voltage and the reference voltage is compared and passed through PI controllers to produce pulse which is given to the switch S_1. The MATLAB software has been selected owing to its good features like its high speed computational accuracy and reliability.

Figure 6 shows the line regulation obtained. When the input voltage is stepped to 16V from 20V, after a small transient occurs, the output voltage is regulated at 325V which is the required output voltage shown in Figure 6 (a). Similarly when the input voltage has a variation of +20%, a small transient occurs at the changing point and output voltage is remain settled at 325V which is the required output voltage shown in Figure 6 (b).

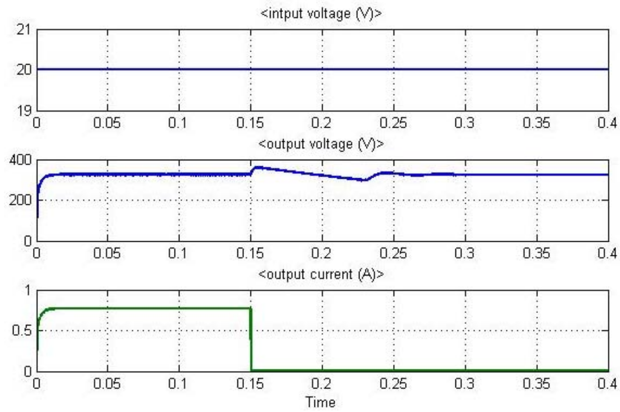


(a)

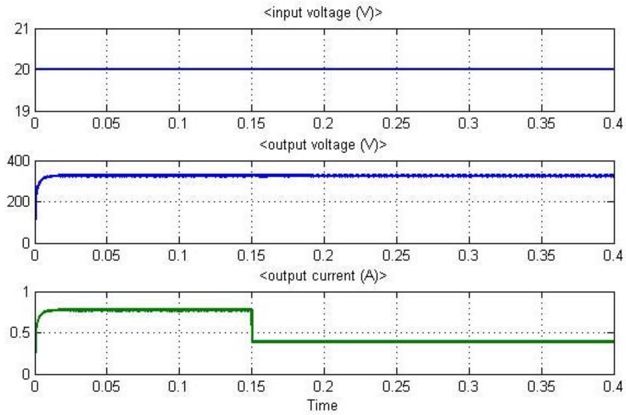


(b)

Figure 6: Line regulation waveforms of the proposed converter. (a) When V_{IN}=16V. (b) When V_{IN}=24V



(a)



(b)

Figure 7: Load regulation waveforms of the proposed converter. (a) When I_O=0A. (b) When I_O=0.385A

Figure 7 shows the load regulation obtained. When the load of the converter changes to no load or half load condition, a small transient will take place in the output voltage and regulated to required 325V. At no load condition, the settling time is about 0.1sec and that for half load condition is about 0.01sec.

Thus these current and voltage waveforms agreed with the operating principles and the steady-state analysis.

6. Comparison with Earliest Scheme

While by comparing with the earliest scheme, the voltage conversion ratio is enlarged from 11 times into 16 times by adding a voltage lift network into the circuit. In earliest proposed scheme, because of the effect of parasitic elements, the power transfer efficiency and output voltage is restricted. But in the newly proposed scheme, by adding voltage lift network, it improves the circuit characteristics. This voltage lift technique provides increase in the conversion with high power density, high efficiency, and cheap topology in simple structure. They also possess high output voltage with small ripples.

7. Conclusion

The derivative of a switched coupled inductor DC-DC step-up converter by using voltage lift network for micro source application is presented in this paper. Voltage lift technique opens a good way to improve the circuit characteristics. High voltage gain is obtained by employing a switched coupled inductor and a switched capacitor in to one converter. The output voltage is enlarged by adding a voltage lift network. This voltage lift network formed by a module with capacitor and diodes. The operating principles and steady state analysis of the converter is also discussed in this paper. This high gain converter provides high power density, high efficiency, and cheap topology in simple structure. The total parts count is only eight. The voltage gain is more than 16 when adding a voltage lift network and the turns ratio of the coupled inductor is three.The voltage lift network possess many advantages including the high output voltage with small ripples. Therefore, these converters can be widely used in industrial applications, especially for high output voltage project. Here the gate signals are generated using PWM control scheme in order to get good voltage regulation.

A 20 to 325V, 250W model of proposed converter is simulated in MATLAB 2013. From the simulation results, it is see that the waveforms agree with the operating principles and steady state analysis. The voltage on the main switch is clamped at 60V; thus, a switch with low voltage ratings and low ON-state resistance RDS (ON) can be selected.

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