High Gain DC-DC Converter Integrating Dickson Charge Pump with Coupled Inductor Technique

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Abstract: *I*n this paper, a novel high voltage gain DC-DC converter based on coupled inductor and voltage multiplier technique is proposed. The benefits of the proposed converter are ultra-high voltage gain, low voltage stress across the power switch and very low input current ripple by employing a low current ripple structure (LCR) at the input side. A low on state resistance ($R_{DS(on)}$) of the power switch can be employed since the voltage stress is a maximum of 25% of the output voltage and the conduction losses of the switch is also reduced. Design of a 1.9kW, 48V at the low voltage side and 430V at the high voltage side is done and verified by simulation. Simulation results show an efficiency of over 93% when operating in continuous conduction mode (CCM).

KEYWORDS: High voltage gain, low input current ripple, coupled inductor, low voltage stress, voltage multiplier

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INTRODUCTION

The world is moving towards the renewable energy for electric power generation since the fossil fuels are depleting at a faster rate and cost of the fossil fuels like gas and petroleum are skyrocketed. Also, the global warming is started to consider as a very serious threat to all the living beings on earth because of the greenhouse gases emitted by the fossil fuels like coal and petroleum. Upon renewable energy sources, Photovoltaic systems have grown tremendous in the recent years. But the voltage obtained from PV is very low (~ 12V – 48V) and is greatly depends on climatic condition. DC-DC converters play an important role in boosting the obtained voltage to the required level. But the gain of the traditional boost converters is limited (<6) and it cannot boost up the voltage at very high level when the solar irradiation is very low or at faulty condition. Hence, high gain DC-DC converters are much needed for the further growth of renewable energy application. Many types of boost converters have been proposed for high voltage gain applications. Topologies include switched capacitor and switched Inductor based techniques [3]-[4], voltage multiplier techniques [5], some interleaved techniques [1]-[2] and coupled inductor techniques [6]-[10]. Each topology has its own advantages and disadvantages. Keeping in mind the advantages and disadvantages of the above-mentioned topologies, a new high voltage gain DC-DC converter is proposed by taking advantage of the coupled inductor and voltage multiplier techniques. The advantages of the proposed converter are presented as follows. (a) It can operate in wide voltage conversion ratio even at low turns ratio of the coupled inductor. (b) The input current ripple is literally zero by employing a low current ripple structure (LCR) which is beneficious for MPPT algorithms which is optimal at continuous input current and it will also enhance the life of Fuel cells. (c) The voltage stress across the main switch is a maximum of 25% which enables us to use a switch with low on state resistance (low $R_{DS(on)}$) which reduces the conduction losses and increase the efficiency of the converter. This paper is organized as follows. The topology and operating principle of the proposed converter is presented in section II. Steady state operation and mathematical modeling is presented insection III. Insection IV, the presented converter is compared with some former high gain DC-DC converters. Simulation results are discussed in section V and conclusion will be drawn in section VI.

OPERATING PRINCIPLE OF THE PROPOSED CONVERTER

The circuit structure of the proposed high gain DC-DC converter is shown in Fig. 1. It consists of an LCR circuit in parallel with the source voltage (Vs) having auxiliary inductance La and capacitance C_L, a coupled inductor modeled as an ideal transformer having primary winding inductance L_1, secondary winding inductance L_2 and magnetizing inductance L_m.

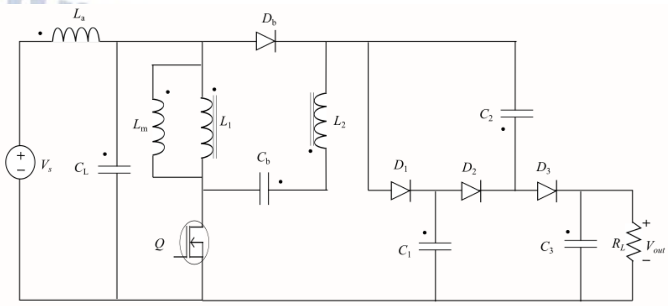


Fig. 1: The circuit prototype of the proposed high voltage gain converter

A blocking capacitor C_b is connected in series with the secondary winding and a diode D_b connecting positive polarity of the primary winding and negative polarity of the secondary winding of the ideal transformer. The circuit has only one power MOSFET switch. Voltage multiplier circuit consists of basic Dickson voltage multiplier having 2 number of diode capacitor cells namely D_1, C_1, D_2 and C_2. Finally, an output capacitor C_3 in parallel with the load. The following assumptions are made for the steady state analysis of the proposed converter. (a) The power switch and diodes are all ideal. (b) The leakage inductance of the coupled inductor is neglected and the coupling coefficient is assumed to be 1. (c) All the passive components are also ideal. The key waveforms of the proposed converter for the continuous conduction mode is illustrated in Fig. 2. Also, the equivalent circuit during Ton and Toff is shown in Fig. 3.

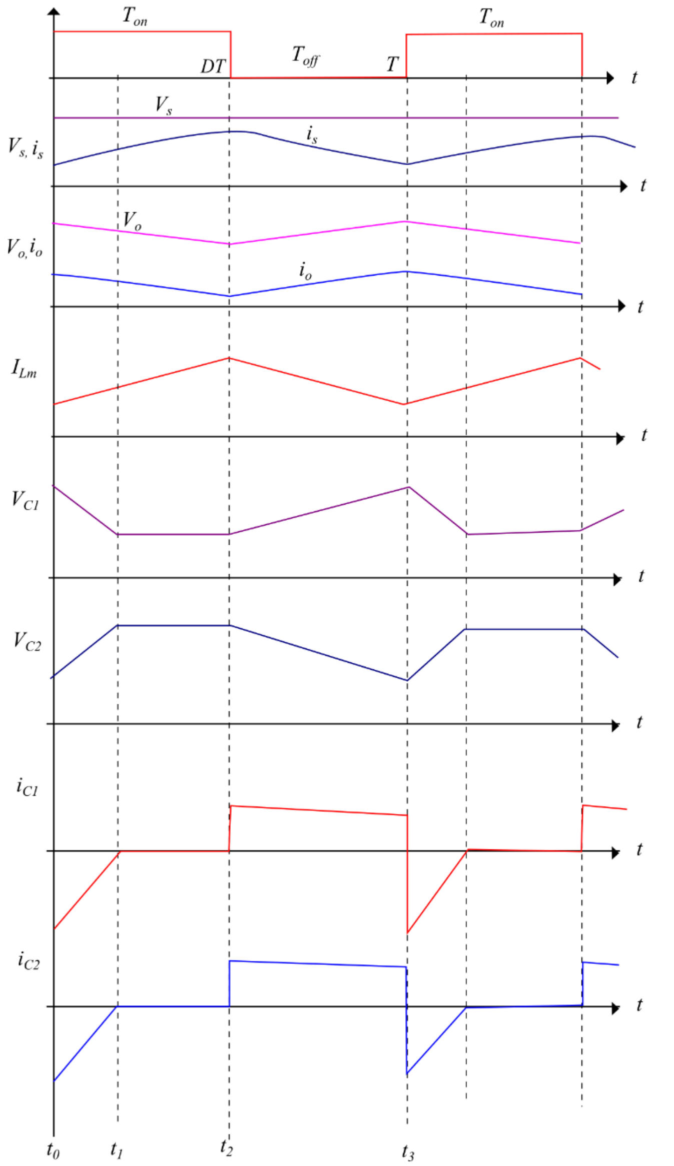


Fig. 2: The key waveforms of thh proposed converter under CCM operation

During T$_{on}$, 0 < t ≤ DT: The sub-circuit corresponding to this interval is shown in Fig. 3(a). At t = t$_0$, the switch Q will be turned on. Diode D$_b$ and D$_2$ forward biased and Diode D$_1$ and D$_3$ is reverse biased. No power will transfer from source to load. Only the energy stored in the capacitor C$_3$ will be delivered to the load which makes the converter to operate in continuous conduction mode. The capacitor C$_1$ which was already got charged during T$_{off}$ and now it will charge the capacitor C$_2$ via the inductor L$_2$ and capacitor C$_b$. The current through the magnetizing inductance will be increased from I$_{Lmin}$ to I$_{Lmax}$.The blocking capacitor C$_b$ is also getting charged. At t = t$_0$, the current through the capacitors C$_1$ and C$_2$ willreach zero and the current through the primary and secondary winding of the ideal transformer will also reach zero. Only the magnetizing inductance current will not be zero and the load current is I$_{c3}$. The voltage across the inductor L$_1$ is

$V_{L1(on)} = V_s(1)$

The voltage across the capacitor C$_b$ is

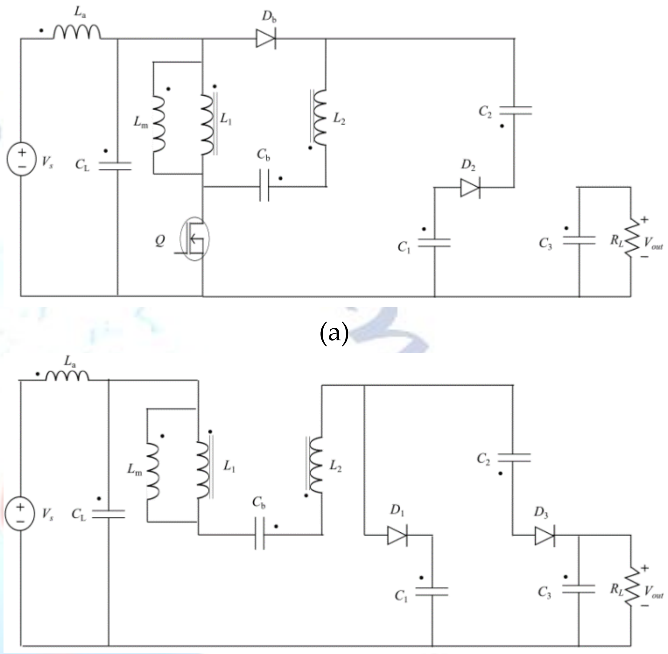
$V_{Cb} = Vs(1+n)$

The voltage across the capacitor C$_2$ is

$V_{C2} = V_{C1} – V_s$

And the output voltage is

$V_0 = V_{c3}$



(a)

(b)

Fig. 3: Equivalent circuit of the proposed converter. (a) during T$_{on}$. (b) during T$_{off}$.

During T$_{off}$, DT < t ≤ T: The sub-circuit corresponding to this interval is shown in Fig. 3(b). At t = t$_2$, the switch Q will be turned off. Diode D$_b$ and D$_2$ are reverse biased. Now, the energy stored in the magnetizing inductance L$_m$, the blocking capacitor C$_b$ and the charge pump capacitor C$_2$ is getting discharged to the load along with the source energy. The capacitor C$_1$ is getting charged and so does C$_3$. The current through the magnetizing inductance will reach from I$_{Lmax}$ to I$_{Lmin}$. The voltage across the inductor L$_1$ is

$$V_{L1} = V_s + V_{Cb} - V_{L2} – V_{C1}$$

To give

$$V_{L1(off)} = \left[\frac{Vs}{(n+1)}\left[\frac{3}{2} + n\right] - \frac{Vo}{2(n+1)}\right] \quad (2)$$

STEADY STATE ANALYSIS OF THE PROPOSED CONVERTER

A. Voltage gain (M)

By applying the volt-sec balance across the inductor L$_1$

V_{L1on}. Ton + V_{L1off}. Toff = 0

Using the relation (1) and (2),

$$VsDT + \left[\frac{Vs}{(n+1)}\left[\frac{3}{2}+n\right] - \frac{Vo}{2(n+1)}\right]T(1-D) = 0$$

The voltage gain of the proposed converter can be calculated as

$$M = \frac{V_0}{V_s} = \left[\frac{2n-D+3}{(1-D)}\right]$$

B. Voltage stress across the Power switch

According to Fig. 3(b), the maximum voltage across the switch Q during T_{off} can be calculated as

$$V_{Qmax} = V_s - V_{L1off} = \frac{Vs}{(1-D)} = \frac{Vo}{2n-D+3}$$

C. Ripple in Magnetizing inductor current (ΔI_{Lm}) and output voltage ($\Delta V_0 = \Delta V_3$)

During T_{on}, the voltage across the Inductance L_m is

$$V_{Lm(on)} = V_s$$

Which gives

$$\Delta I_{Lm} = \frac{DVs}{fL_m}$$

During T_{on}, the current through the capacitor C_3 is

$$I_{C3(on)} = -I_0 = C_3\frac{\Delta V_{C3}}{DT}$$

Which gives

$$\Delta V_{C3} = \frac{DI_0}{fC_3}$$

IV. COMPARISON WITH OTHER TOPOLOGIES

The key parameters of the proposed converter and the other high voltage gain DC-DC converters are compared and presented in Table I. The proposed converter offers high voltage gain than most of the counterparts. The input current ripple is lowest among all other converters and the voltage stress is a maximum of 25% which results in low conduction losses by using low on state resistance (low $RDS_{(on)}$) power switch.

V. SIMULATION RESULTS

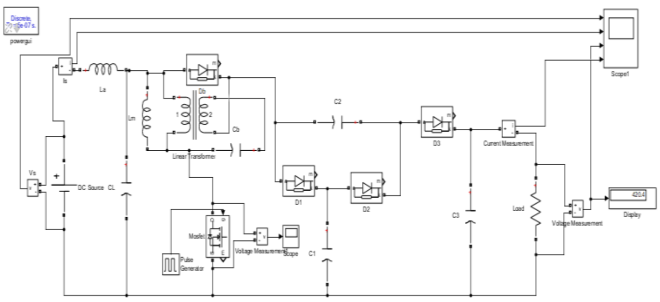
The key MATLAB Simulink waveforms are shown in Fig. 4. Table II shows the parameter and its specifications of the Simulink prototype. The results show that the converter output voltage is 420V (for 432V theoretical output voltage, some volts drop at the low on state resistance MOSFET switch) at 48 V input supply at 50% duty ratio (voltage gain = 8.75). The input current is continuous with literally zero ripple and the ripple in output current as well as output voltage is less than 1%. The maximum voltage across the switch is measured as 97V which is less than 25% of the output voltage. The efficiency achieved at 1.8 kW is 93.65%. Similarly, the converter can be able to achieve a gain of 14.06 at 70% duty ratio and still the efficiency is over 90%.

TABLE I: PERFORMANCE COMPARISON BETWEEN THE PROPOSED CONVERTER AND OTHER HIGH VOLTAGE GAIN CONVERTERS

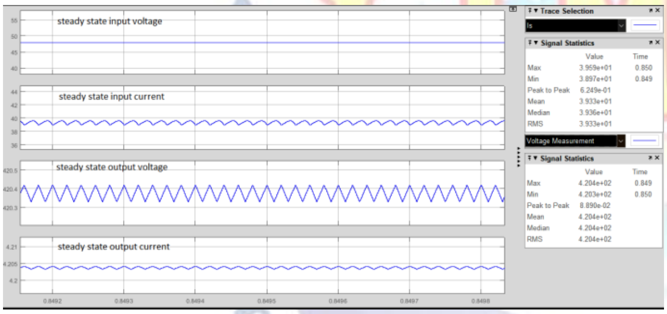
Reference	Number of components				Voltage gain	Voltage stress of switch / V_0	Input current ripple
	Switch	Diode	Capacitor	Inductor			
[5]	1	3	3	1	$\frac{1+n}{2(1-D)}$	$\frac{2}{1+n}$	medium
[17]	1	4	5	2	$\frac{2+n+D}{(1-D)}$	$\frac{1}{2+D+n}$	low
[16]	4	0	5	1 (coupled) +2	$\frac{2+n}{(1-D)}$	$\frac{1}{2+n}$	low
[8]	2	2	4	2 (coupled)	$\frac{2n-1}{(1-D)(n-1)}$	$\frac{n-1}{(2n-1)}$	low
[6]	3	0	3	2 (coupled)	$\frac{2+n-D}{(1-D)}$	$\frac{1}{2-D+n}$	high
Proposed converter	1	4	5	2 (coupled) +1	$\left[\frac{2n-D+3}{(1-D)}\right]$	$\frac{1}{2n-D+3}$	Very low

TABLE II: PARAMETERS AND SPECIFICATIONS OF THE SIMULINK PROTOTYPE

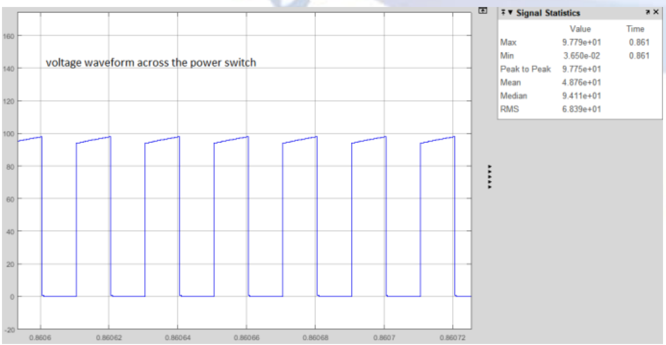
Parameter	Simulink
Voltage	V_s = 48 V and V_0 = 420 V at D = 50 %
Load	1.8 kW
Components	L_a = 10 μH, C_L = 100 μF, L_m = 1 mH, C_b = C_1 = C_2 = 47 μF, C_3 = 470 μF
Switching frequency and turns ratio	50 kHz, turns ratio (n)= 1



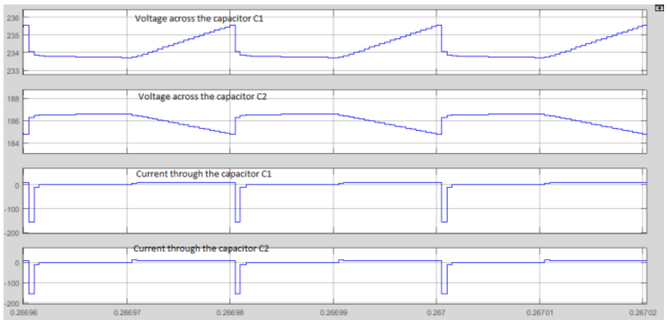
(a) MATLAB Simulink diagram



(b) Input and output voltage and current



(c) Voltage waveform across the power switch



(d) Voltage and current across the charge pump capacitors

Fig. 4. Simulink diagram and the key waveforms of the proposed converter

CONCLUSION

A new high gain DC-DC converter is presented in this paper. The converter input current is continuous with very low ripple by the use of LCR structure. The gain of the converter is also very high at low duty and turns ratio. It is shown that the voltage stress across the power switch is the lowest among the other former DC-DC converters which results in lower conduction losses and the cost of the converter is also reduced by using the low $R_{DS(on)}$ power switch. Mathematical modeling for voltage gain and voltage stress is done and it is verified by the simulation results. This converter can be used in standalone PV fed low power (<5kW) domestic applications, Fuel cell driven vehicles and it can also boost up the voltage from the renewable energy sources to the grid voltage and directly feed it to the DC grid.

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