A 3-Level Boost Converter with High Voltage Gain and High Efficiency

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Abstract— A three level DC-DC Boost Converter for High Gain Applications is proposed in this report. This converter is based on one inductor, one switch, 2N-1 diodes and 2N-1 capacitor, for an Nx converter, it is a boost converter able to control and maintain the same voltage in all the N output levels, and able to control the input current. The salient features of such converters are high voltage gain without using extreme duty ratio, use of few components and self-DC-link balancing. In these converter topologies each device blocks only one voltage level.

Key words: Multilevel Boost Converter (MBC), Voltage Multiplier, Voltage gain, Self-balancing

I. INTRODUCTION

DC-DC converter is an electronic circuit or electromechanical device which converts a source of direct current from one voltage level to another. It is a type of electric power converter. Power levels range from very low to very high. In order to adapt the output voltage of the energy supplies/storage systems to the medium voltage level, boosting of the DC voltage is required. For large voltage step-up ratios this task is advantageously performed by DC-DC converters based on galvanically isolated transformers. However, in case of smaller step-ratios, the galvanic isolation is not mandatory, then a much higher efficiency and power density can be achieved with non-isolated boost converter systems.

In recent year's transformer-less high step-up converters have enormous applications in the power industries such as renewable energy systems. A boost converter or step-up converter is a DC-DC power converter steps up voltage (while stepping down current) from its input to its output. The gain ratio of simple boost converter is low, also voltage stress across switch is same as output voltage. Also, their step-up capability is restricted due to number of power switches. A boost converter must operate at extreme duty ratios to achieve high voltage gain. As the output voltage increases, the voltage rating of the semiconductor switching device increases and at high duty ratios the conduction losses of semiconductor device can make a more significant impact to the performance of the system.

The voltage gain can be extended, and the current ripple can be further reduced to satisfy the high-step-up requirements by employing the cascade structure. Theoretically, larger conversion ratios can be obtained by properly adjusting the modulating control signal of the converter. The turn-on time and turn-off time of the active switch now play an important role for the attainable duty ratio and, consequently, in the conversion ratio. For the above reasons, it is better to select an operating point in the midrange, D=0.5. To get high voltage gain several boost converter can be cascaded but at the expense of reduced efficiency. The efficiency of cascaded boost converter decreases because for the cascaded topology, active gate control is required for both the switches to ensure equal voltage sharing between all the devices at the switching instance which in turn increases the switching losses. Moreover the controllers should be synchronized and should maintain the stability which is of great concern. In addition the output rectifier of second boost stage undergoes severe reverse recovery problem which in turn degrades the efficiency and causes EMI noise.

As with the inverter systems, multilevel boost converter concepts basically enable to use faster semiconductor devices. These results in a higher efficiency especially if a high operating frequency is required in order to achieve higher power densities and to avoid acoustic noise. The DC-DC multilevel boost converter is a pulse-width modulation based DC-DC converter, which combines the boost converter and the switched capacitor function to provide different output voltages and a self-balanced voltage using only one driven switch, one inductor, 2N-1 diodes and 2N-1 capacitors for an Nx MBC. It is a boost converter PWM controlled and able to maintain the same voltage in all N output levels and able to control the input current. The major advantages of this topology are a continuous input current, a large conversion ratio without extreme duty cycle and without transformer, which allow high switching frequency. It can be built in a modular way and more levels can be added without changing the main circuit; it provides several self balanced voltage levels and only one switch is necessary. In other words, the voltage across every capacitor at the output of the MBC tends to be equal. Even during transient conditions these voltages are similar. It is proposed to be used as DC link in applications where several controlled voltage levels are wanted with self balancing and unidirectional current flow, such as PV or fuel cell generation systems with multilevel inverters. In this paper, a 3-Level Boost Converter is considered.

II. 3-LEVEL BOOST CONVERTER

The multilevel boost converter which combines the boost converter and the switched capacitor function to provide an output of several capacitors in series with the same voltage and self-balanced voltage is illustrated in Fig.1.

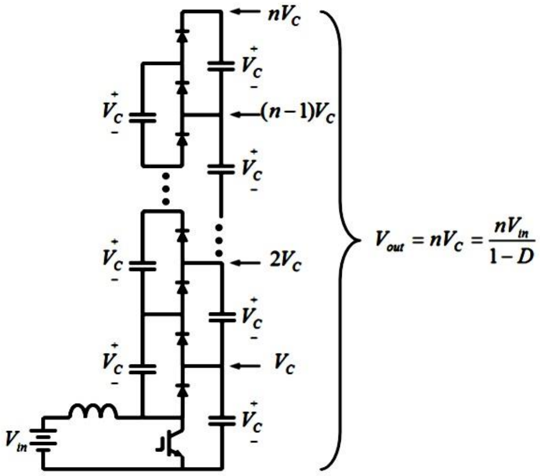

Fig. 1: Multilevel Boost Converter

III. WORKING OF A 3-LEVEL BOOST CONVERTER

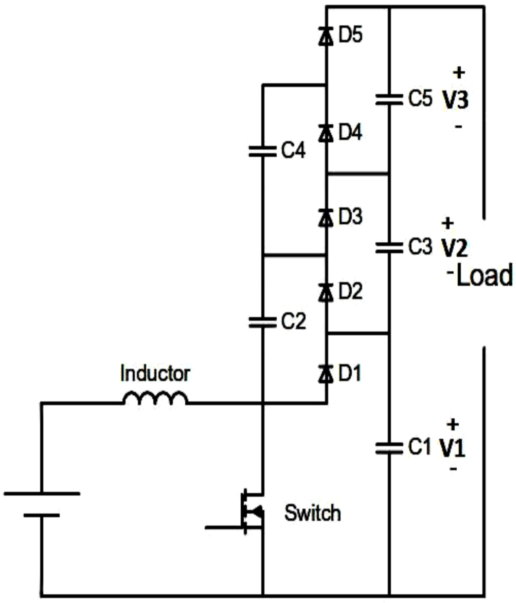

Fig. 2: 3-Level Boost Converter

The 3-level boost converter studied here is as shown in fig. 2. When the switch is ON, the inductor is connected to the voltage source. If C2's voltage is smaller than C1's voltage, C1 charges C2 through the diode D2 and the switch. Simultaneously, if the voltage across C2+C4 is smaller than the voltage across C1+C3, C1 and C3 charge C2 and C4 through the diode D4. In the same time the capacitor voltage across C1+C3+C5 discharges in the load.

Besides that, when the switch turns off, the diode D1 turns on and the inductor charges the capacitor C1 until the voltage on the capacitor C1 equal to the summation voltage on the voltage source and the inductor voltage. After that, the diode D3 turns on so the voltage source, the inductor and capacitor C2 charging the capacitor C1+C3 through it. Besides that, the voltage on the C1+C3 is equal to the summation voltage on the voltage source, the voltage on the inductor and the voltage on the capacitor C2, the diode D3 turns off and the diode D5 turns on so the voltage source, inductor and capacitors C2 and C4 will charging capacitors C5, C3, C1 until the voltage on it equal to the summation of the voltage on the voltage source, inductor and capacitors C2+C4.

IV. CONVERTER ANALYSIS

A. Switch and Diode Voltage Limitations:

In actual implementations the switches and diodes voltage drop must be taken into account since it avoids capacitors to be charged to $V_C$this effect is studied in the present section. For simplicity, the voltage drop in switches and diodes is assumed to be equal to $V_{d.}$ The voltage across capacitor C2 is,

$$V_{C2} = V_{C1} – V_{Switch} - V_d$$

As per the assumption,

$$V_{C2} = V_{C1} – 2\ V_d$$

Similarly the voltage across capacitor C3 is,

$$V_{C3}= V_{C1} – 4\ V_d$$

The voltage drop in the voltage multiplier does not depend on the level after the second level, and it can be seen that all capacitors after the second level are charged to V_{C1} – 4 $V_{d..}$ The expression of the output voltage for the circuit,

$$V_{out}= V_{C1} – 12\ V_d$$

Finally, the output voltage general expression in an Nx multilevel boost converter is,

$$V_{out}=N\ V_{C1} – (N\text{-}1)\ V_d$$

Where V_C is the voltage across each capacitor, and follows the traditional boost converter equation.

B. Losses Taken Into Account:

In this section the boost ratio will be analyzed, which is very important because the inductor losses limit the theoretically maximum boost ratio. The total output voltage is N times V_C and the new voltage gain can be expressed as

$$\frac{V_o}{V_{in}} = N\,\frac{1}{1-D}$$

The input DC current can be expressed in terms of the output current and input-output voltage as

$$V_{in}\,I_{in} = V_{out}\,I_{out} = \frac{N^2 V_C}{R_0}$$

$$I_L = \frac{V_C N^2}{(1-D)R_0}$$

The energy stored in an inductor over one complete cycle is zero. Thus the boost ratio for the novel topology may be expressed as,

$$\frac{V_{in}}{V_{out}} = \frac{1}{\frac{(1-D)}{N}+\frac{NR_L}{(1-D)R_0}}$$

Where, V_{in} is the input voltage, V_{out} is the output voltage, D is the duty ratio, R is the load resistance, V_C is the voltage across each capacitor, f_s is the switching frequency, N is the number of output levels, V_{switch} is the voltage across the switch, V_d is the diode voltage drop.

C. Design Considerations:

The transfer function of the conventional boost converter is,

$$\frac{V_o}{V_{in}} = \frac{1}{1-D}$$

The transfer function of the multilevel boost converter is,

$$\frac{V_o}{V_{in}} = \frac{3}{1-D}$$

The MBC has a high conversion ratio without extreme duty cycle. The difference between two equations is the number of levels of the multilevel boost converter. The inductor size is decided such that the change in inductor current is no more than 10% of the average inductor current.

We know that, the power developed and power delivered are equal. Therefore,

$$V_{in}\,I_{in} = V_O I_O$$

$$L_{min} = \frac{R_{load}\,(1-D)^2 D}{2N^2 f_s}$$

Where, R = $\frac{V_O}{I_0}$ and L = 10 L_{min}

The design criterion for capacitors is that the ripple voltage across them should be less than 0.1%. Equation gives the value of the capacitor to be used in the MBC. As shown from this equation, the capacitor size is same as the capacitor size of the conventional boost converter.

$$C = \frac{DV_O}{\Delta V_C f_S R}$$

Where, Vin is the input voltage, Vout is the output voltage, D is the duty ratio, R is the load resistance, Vc is the voltage across each capacitor, fs is the switching frequency.

V. DESIGN AND SIMULATION

Parameter	Values
Input Voltage, Vin	17 V
Output Voltage, Vout	75 V
Output Power, P	40 W
Switching frequency, fs	10 kHz
Inductance, L	1.15mH
Capacitance, C	217 uF

Table 1: Design Specifications

The MATLAB SIMULINK model of the 3–level boost converter is as shown in fig. 3. An output voltage of 73 V is obtained for a 17 V input voltage. The voltage across each of the output capacitor C1, C3, C5 are the same and is equal to 24.3 V.

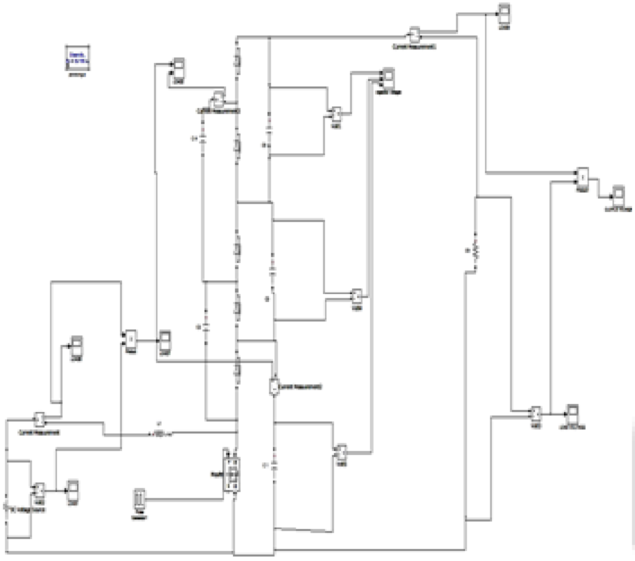

Fig. 3: MATLAB simulation of a 3-Level Boost Converter

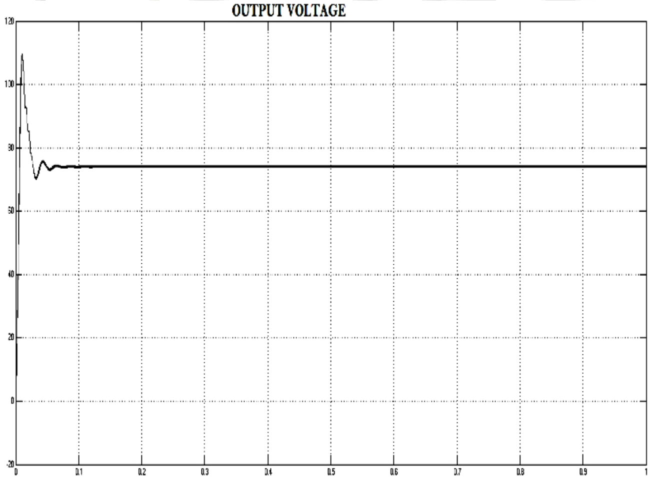

Fig. 4: Output voltage waveform of a 3-Level Boost Converter

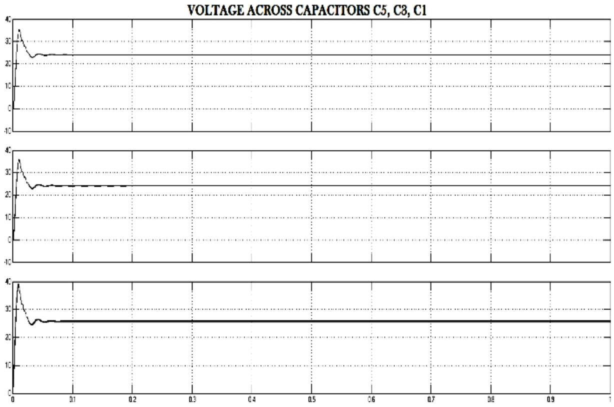

Fig. 5: Capacitor voltage waveform of a 3-Level Boost Converter

VI. EXPERIMENTAL DETAILS

Hardware setup of the multilevel boost converter is implemented to power a 40 W system. The MBC provides an output voltage of 72.7 V for an input 17 V. The completed laboratory set-up of multilevel boost converter circuit is as shown in Fig 6. The converter parameter values and the results are shown in Table II.

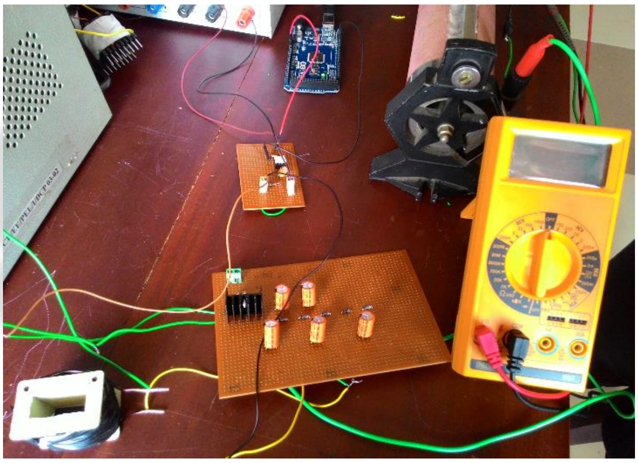

Fig. 6: Experimental Setup of the Prototype

Parameter	Values
Input Voltage, Vin	17 V
Output Voltage, Vout	72.7 V
Switching frequency, fs	10 kHz
Inductance, L	1.15 mH
Capacitance, C	220 uF
Load Resistor	150 ohm

Table 2: Experimental Details

VII. CONCLUSION

A new high efficiency and high voltage gain DC-DC multilevel boost converter has been designed. It is proposed to be used as DC link in applications where several controlled voltage levels are needed with self balancing feature and it is based on the multilevel converter principle, where each device blocks only one voltage level. The proposed converter is designed, modelled and simulated. The MBC presents several advantages in comparison to the conventional boost converter and other topologies. The major advantages of this topology are a continuous input current, a large conversion ratio without extreme duty cycle and without transformer, which allow high switching frequency. It can be built in a modular way and more levels can be added without changing the main circuit and it provides several self balanced voltage levels and only one switch is necessary.

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