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Analysis of New Flexible Hybrid Boost Converter for Low Voltage Sources

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***Abstract-* : This paper presents a new hybrid boosting converter used to increase the input dc voltage. In existing method hybrid boosting converter used with one switch in the converterand produces boosted output. Here the even order HBC topology is explained and simulated for odd order topology to show the difference of both the orders. The odd order topology gives output boosted for high value of about 290V from 48V input.**

Keywords —*HBC, Bipolar Voltage Multiplier (BVM), single-switch single inductor, nature interleaving, renewable energy*.

I. INTRODUCTION

The recent sharp increases in the prices of oil, natural gas, uranium and coal underline the importance for all countries to focus on development of alternative energy resources. For developing countries, these price increases can have ruinous economic consequences; for many countries already plagued by poverty this means a choice between fuel and food, health care, education and other essentials. Renewable energy resources need priority because: 1) the overwhelming scientific evidence that anthropological emissions of greenhouse gases from carbon combustion threaten catastrophic results from rapid climate change; 2) the severe health and environmental consequences from fossil fuel combustion being experienced in every major developing country city; and 3) the high cost, environmental damages and security threats of nuclear power. In recent years the need for renewable energy system calls for new generation of high gain DC/DC converters with high efficiency and low cost. The front end of “Plug and Play” PV system usually demands step-up converter which is capable of boosting the voltage from 35V to 380V with regulation capability due to the low terminal voltage and the requirement of MPPT tracking function for single PV panel. In order to achieve high conversion ratio with high efficiency there have proposed many techniques. Among them, switched-capacitor structure, tapped/coupled inductor based technique, transformer based technique voltage multiplier structure or combinations of them attracted significant attentions. Each technology has its unique advantages and limitations. In this paper, gain enhancement technology based on modification of traditional boost converter while maintaining single-inductor and single switch is investigated, targeting at simplifying the circuit design, reducing the cost, satisfying the demands of normal high gain applications, and facilitating mass production. The idea of gain enhancement from a boost converter started from cascaded boost and quadratic boost. But cascaded boost converter increased the power processing stages and reduced the efficiency. The quadratic boost converter achieved higher voltage gain with a single switch, yet introduced high component voltage stress. In addition, they both employed extra switch or inductor. Many gain extension methods of boost converter by adding only diodes and capacitors were investigated in the past. The method of combining boost converter with traditional Dickson multiplier and Cockcroft-Walton multiplier to generate new topologies were proposed such as topologies in Fig1 to 5. Besides, two switched capacitor cells were proposed and numerous topologies were derived by applying them to the basic PWM DC-DC converters. A modified voltage-lift cell was proposed in and the topology was produced. The different voltage boosting techniques are explained in brief below.

A. Traditional Boost converter

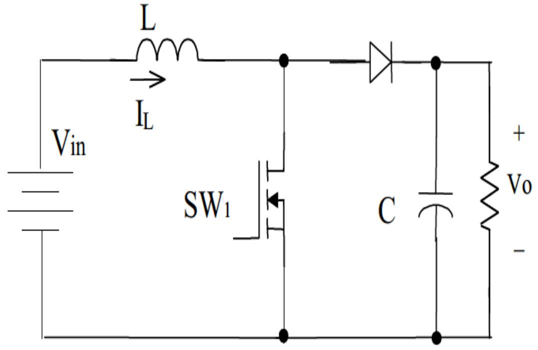


Fig 1. Traditional boost converter

The traditional boost converter shown in the figure above is capable of stepping up the input voltage upto certain extent when a high voltage gain is required then its boosting capacity is reduced and also its efficiency is reduced .The conversion ratio of the traditional boosting converter is given by

$$\frac{V_0}{V_{in}} = \frac{1}{1-D}$$

The efficiency is reduced because of a high duty cycle is required to obtain high efficiency so due to high duty cycle all the power delivered to the load is done in a short period of time. Therefore in order to have a better efficiency the duty cycle must be reduced which inturn reduces boosting capability.

So in order to overcome this problem many other topologies were analyzed

B. Tapped Inductor Boost Converter

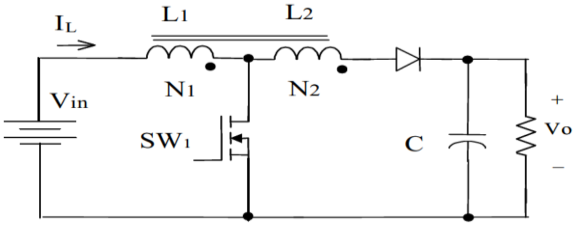


Fig 2.Tapped inductor boost converter

This is a different approach to obtain the desired high boosting capability resulting in simpler converter with high efficiency and without the complexity of stages integration or complex regenerative snubber. It can achieve the boosting capability without a high duty cycle and also stress on the active semiconductor is also reduced. The only disadvantage is it requires snubber circuit to handle leakage problem. Meanwhile the different current ratings of different windings and turns ratio design complicate the circuit manufacture.

C. Switched Capacitor Converter

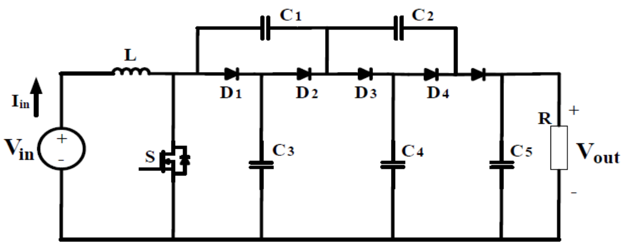


Fig 3.Switched capacitor converter

They are a special type of converters that do not require an inductor and are also known as inductorless converters or charge pumps. With the resistors connected in the load current will flow from capacitors but the output voltage will be largely unaffected if the switching frequency is sufficiently high and capacitor charges are replenished in short time intervals. The output will be less than $2V_s$ for real devices because of voltage drops in the circuit. The disadvantage of this topology is it has serious problems of pulsating current and poor regulation capability.

D. Cockcroft- Walton Converter

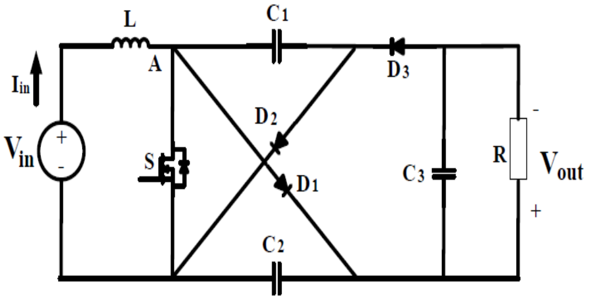


Fig 4.Cockcroft Walton converter

This is a transformerless DC-DC converter topology due to the absence of transformer it has high efficiency due to the absence of leakage inductance. This topology uses transformerless DC-DC converter with nine stage Cockcroft-Walton voltage multiplier. This topology reduces the switching losses and stress on the switches. The voltage multiplier boosts the voltage without increasing the switch voltage and diode voltage and also at low duty cycle. Here the high gain DC voltage is obtained just by increasing the stages and not the circuit components. By controlling the duty ratio the regulation of output voltage is possible.

E. Super lift Converters

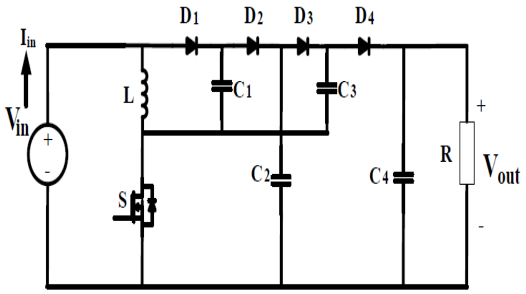


Fig 5. Superlift converters

These are a special type of converters that implements the increasing of voltage in geometric progression. Its efficiency enhances the voltage transfer gain in power series. In this topology very large output voltage is easily obtained. These type of converter topologies are widely used in industrial applications.

F. A New HBC Converter

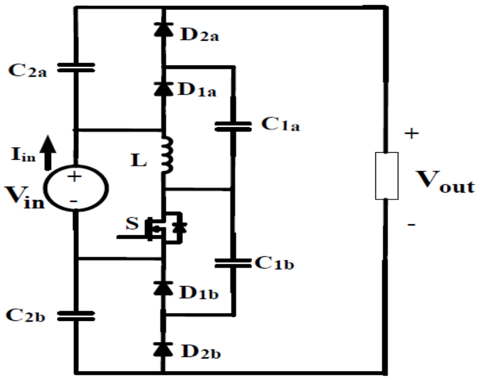


Fig 6.Hybrid boosting converter

In concern with achieving of high conversion ratio with high efficiency many high gain enhancement techniques were investigated. Inspired by all the mentioned topologies a new Hybrid Boosting Converter (HBC) with single switch and single inductor is proposed by employing Bipolar Voltage multiplier in this paper. The second order HBC is as shown in the figure above. The proposed converter decreases the size of the high voltage rating output filter capacitor and exhibits the nature interleaving operation characteristics. In comparison with all the said topologies, this HBC topology has smaller output ripple and higher components utilization rate with respect to conversion ratio. The proposed topology has achieved smaller ripple with single switch and single inductor while maintaining high voltage gain.

II. PROPOSED GENERAL HBC TOPOLOGY AND ITS OPERATIONAL PRINCIPAL

The proposed HBC is shown in Fig 6. There are two versions of HBC, odd-order HBC and even-order HBC as shown in Fig 7 and 8. The even-order topology integrates the input source aspartoftheoutputvoltage,leadingtoahighercomponentsutilizationratewithrespecttothesamevoltagegain.However,theysharesimilarothercharacteristicsandcircuitanalysis method. Therefore only even order topology is explained.

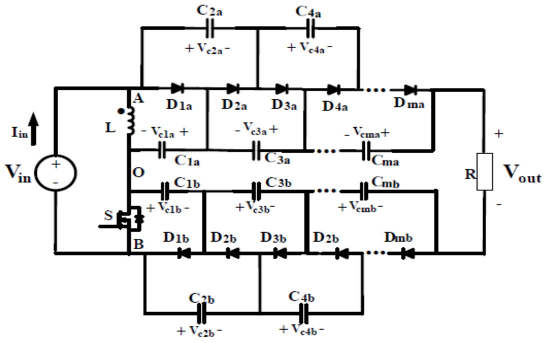


Fig 7.Odd order HBC converter

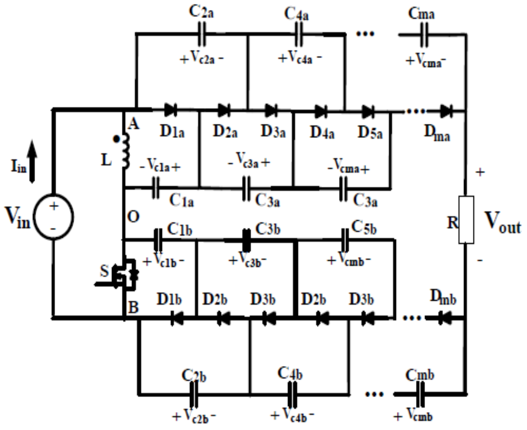


Fig 8. Even order HBC converter

A. Inductive switching core

In a HBC topology, the inductor, switch and input source serve as an “inductive switching core”, shown as Fig 9. It can generate two “complimentary” PWM voltage waveforms at port AO and port OB. Although the two voltage waveforms have their individual high voltage level and low voltage level, the gap between two levels is identical, which is an important characteristic of inductive switching core for interleaving operation.

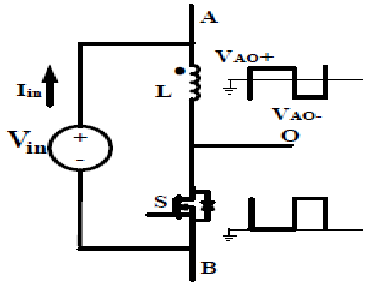


Fig 9. Inductive switching core

B. Bipolar voltage multiplier

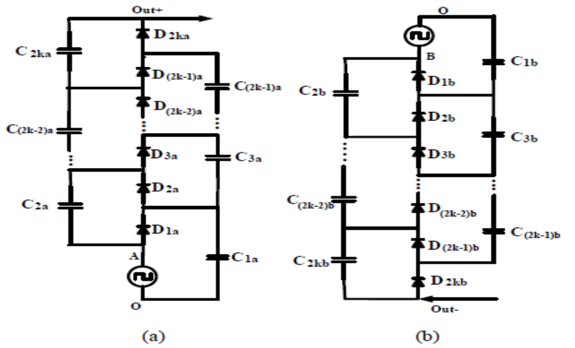


Fig 10. Bipolar voltage multiplier

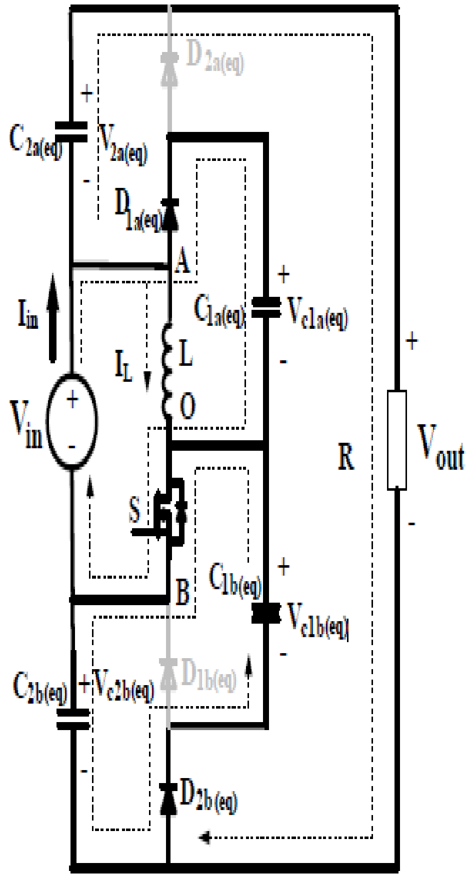
A bipolar voltage multiplier is composed of a positive multiplier branch and a negative multiplier branch, shown in Fig 10. Positive multiplier is same as traditional voltage multiplier while the negative multiplier has the input at the cathode terminal of cascaded diodes, which can generate negative voltage at anode terminal.

By defining the high voltage level at input AO as V_{OA} , the low voltage level as V_{OA}+ , and the duty cycle of high voltage level as D, the operational states of the even-order positive multiplier is derived and illustrated as following:

C. Operation principle of General basic HBC

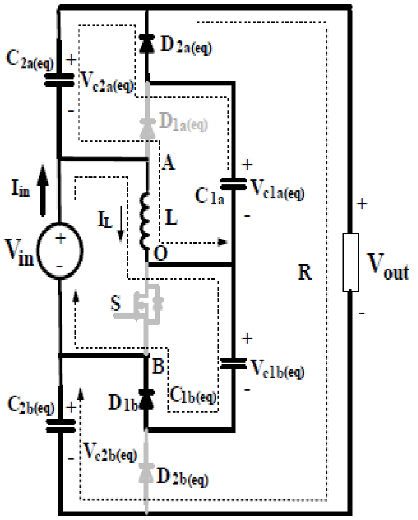
Based on the simplification method discussed in previous section, the general even-order HBC in Fig.8 can be simplified to an equivalent HBC circuit, shown as in Fig (a).

Careful examination of the topology indicates that the two “boost” like sub-circuits are intertwined through the operation of the active switch S. The total output voltage of HBC is thesum of the output voltage of two boost sub-circuits plus the input voltage. Three operation states are described as Fig 11 (a), (b) and (c).



(a)

1) State 2[DTs,(D+D1)Ts]:



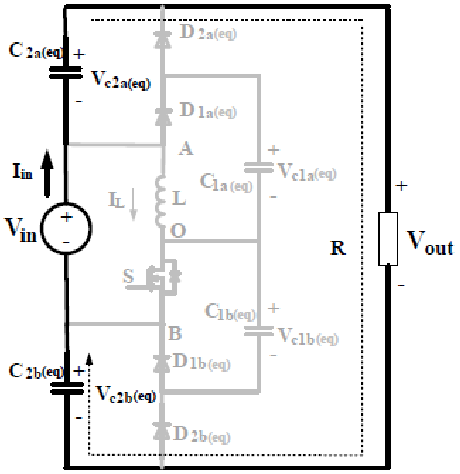
(b)

As illustrated in Fig, when S is turned off, the inductor current will free wheel through diodes and .The inductor is shared by two charging boost loops. In the top loop, capacitor is releasing energy to capacitor and load at the same time. In the bottom loop, input source charges capacitor through the inductor L. During this time interval, voltage generated at AO and OB is expressed as following based on inductor balance principal:

$$V_{AO} = -V_{in}\frac{D}{D_1}$$

$$V_{OB} = V_{in}\frac{(D + D_1)}{D_1}$$

2).State 3[(D+D1)Ts,Ts]:



(c)

Under certain conditions, the circuit will work under DCM operation mode, thus the third state in Fig. 11(c) appeals. At this state, the switch S is kept off. The inductor current has dropped to zero and all the diodes are blocked. The capacitor and are in series with input source to power the load. During this time interval, voltage generated at port AO is zero while at OB is $V_{in.}$

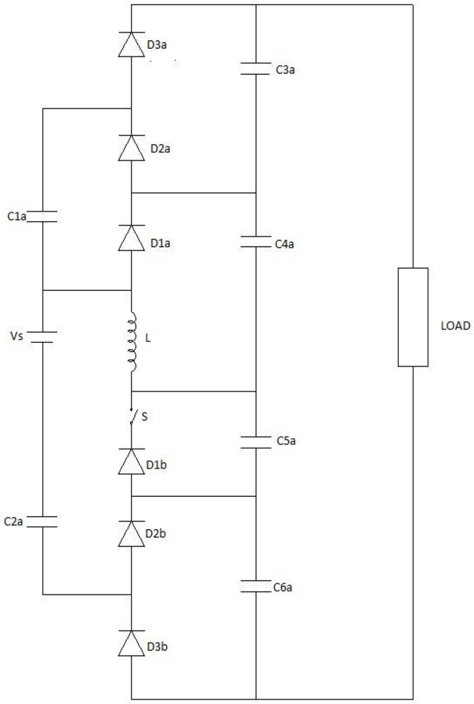


Fig 12. Equivalent odd order HBC

III. CONVERTER PERFORMANCE ANALYSIS

A. Component stress analysis

Detail analysis of components stress for the converter provides solid reference for components selection and optimization. The components stress is estimated in this section.

1) Diodes and Switch:

According to the charge balance law of flying capacitors, all the diodes and have the same average current during one switching period. The average current during conduction state is used to calculate here. The current waveforms of diodes and switch are shown in figure. Their current stress and voltage stress are listed in below table.

Table 1: Component Stress

	$V_{\max}$	I_{ave}	I_{rms}
S	$\frac{V_{in}}{D'}$	$\frac{2kI_a}{D'}$	$2k\frac{I_O}{D'}\sqrt{D}$
$D_{ia}(i=1,3...2k-1)$ $D_{ib}(i=2,4...2k)$	$\frac{V_{in}}{D'}$	I_0	$\frac{I_O}{\sqrt{D}}$
$D_{ia}(i=2,4...2k)$ $D_{ib}(i=1,3...2k-1)$	$\frac{V_{in}}{D'}$	I_0	$\frac{I_O}{\sqrt{D'}}$
C_{ia}	V_{in}	0	$I_O k\sqrt{\frac{1}{DD'}}$
$C_{ia}(i=3,5...2k-1)$	$\frac{V_{in}}{D'}$	0	$(k-\frac{i-1}{2})I_O\sqrt{\frac{1}{DD'}}$
$C_{ib}(i=1,3...2k-1)$	$\frac{V_{in}}{D'}$	0	$(k-\frac{i-1}{2})I_O\sqrt{\frac{1}{DD'}}$
$C_{ia}(i=2,4...2k)$	$\frac{V_{in}}{D'}$	0	$((k-\frac{i}{2})\frac{I_O}{D}+I_O)\sqrt{\frac{D}{D'}}$
$C_{ib}(i=2,4...2k)$	$\frac{V_{in}}{D'}$	0	$((k-\frac{i}{2})\frac{I_O}{D'}+I_O)\sqrt{\frac{D}{D'}}$.

2) Capacitors:

According to the analysis of bipolar voltage multiplier in section II, the flying capacitors that are closer to inductive switching core have larger charging or discharging current, which exhibit larger voltage ripple. Their average charging and discharging current can be used to estimate the RMS current, which is useful to evaluate power loss of each capacitor. The expressions of RMS current for each capacitor in a 2kth-order TBSC are also given in table.

B. Comparison of proposed HBC with previous converters

In order to distinguish the proposed HBC converter, a comparison is carried out between the second-order HBC converter and several previous published converters with single inductor and single switch. All capacitors are assumed to have the same value C for easier comparison. The voltage gain, component count, as well as normalized switch stress and normalized output ripple are all listed for each topology in Table III. The proposed HBC has good gain boosting capability. However, it's difficult to judge the performance of each configuration merely based on the level of its gain curve, especially with consideration of different components count for different topologies. Most of the topologies can extend their gain by adding more stages with a larger number of capacitors and diodes. Therefore, more details should be taken into consideration to evaluate topologies, such as total normalized capacitor voltage rating and normalized output voltage ripple.

For the high gain DC-DC converters with single switch and inductor, a critical aspect to realize high power density and low cost is to decrease the physical size of capacitors. Diodes usually have comparably much smaller volume, whose effect to the power density is neglected in this comparison. The voltage rating and capacitance value are the primary factors that affect the size of each capacitor. In order to compare the density of each topology with same gain, the normalized voltage stresses of capacitors for each topology are calculated in Table II. The normalized voltage stress for a capacitor is defined by the actual voltage stress of the capacitor divided by the output voltage. The total normalized capacitor voltage stress is the sum of all normalized capacitor voltage stress, which takes into account the capacitor number and voltage rating requirement.

Compared with other listed topologies, the proposed second order HBC has lowest total capacitor voltage stress in a wide range of duty cycle. This result shows the superiority of proposed structure for high power density design.

In addition to the normalized capacitor voltage stress comparison, the normalized output ripple compared according to Table III. Among all the converters considered, the proposed HBC structure has the lowest ripple in the duty cycle range of [1/3, 2/3]. When duty cycle ranges are higher than 2/3, only cuk derived converter and zeta derived converter shows smaller ripple theoretically. However, under this condition, cuk converter and zeta converters exhibits much larger normalized total capacitor voltage stress and weaker gain boosting capability. It should be pointed out that although the proposed HBC structure has the advantages in high power density and low cost design, it also has the intrinsic issue of uncommon ground between source and load, which may limit its applications in areas where common ground are not required between input and ouput. Besides, due to direct connection between the input and output, the audio susceptibility may be an issue, which may require an input filter and fast control loop.

Table-2: Comparison of Normalized Capacitor Voltage Stress For Converter

Fig. 1	C1	C2	C3	C4	C5	Total
(a)	1/3	1/3	1/3	2/3	1	8/3
(b)	1/3	1/3	1/3	1/3	1/3	5/3
(c)	$\frac{1-D}{3-D}$	$\frac{2-D}{3-D}$	$\frac{1-D}{3-D}$	1	0	$\frac{8-4D}{3-D}$
(d)	1/3	1/3	1/3	1/3	1/3	5/3
(e)	1/2	1/2	1	0	0	2
(f)	$\frac{D}{1+D}$	$\frac{D}{1+D}$	1	0	0	$\frac{1+3D}{1+D}$
(g)	D/2	1/2	1	0	0	$\frac{3+D}{2}$
(h)	$\frac{1-D}{3-D}$	$\frac{1}{3-D}$	$\frac{1}{3-D}$	$\frac{1}{3-D}$	0	$\frac{4-D}{3-D}$

Table-3: Comparison of Proposed Second Order HBC and other Converters

Fig. 1	Converters	Voltage gain	Diodes	Capacitors	$M_{c\_stress\_norm} = V_{c\_stress} / V_{out}$	$M_{ripple\_norm} = \Delta V_{out} / \frac{V_{out}T_s}{R_L C}$
(a)	Boost+Dickson Multiplier[16]	$\frac{3}{1-D}$	5	5	1/3	D
(b)	Boost+Cockcroft Walton Multiplier[16]	$\frac{3}{1-D}$	5	5	1/3	$3+3D$
(c)	Super-lift Converter[18]	$\frac{3-D}{1-D}$	4	4	1/(3-D)	D
(d)	Multilevel Boost Converter[21]	$\frac{3}{1-D}$	5	5	1/3	$3D$
(e)	Cuk-derived Converter[22]	$-\frac{2}{1-D}$	3	3	1/2	$1-D$
(f)	Zeta-derived Converter[22]	$\frac{1+D}{1-D}$	3	3	1/(1+D)	$1-D$
(g)	Modified voltage Lift Converter[23]	$\frac{2}{1-D}$	3	3	1/2	D
(h)	Proposed HBC	$\frac{3-D}{1-D}$	4	4	1/(3-D)	$\lvert 2D-1 \rvert$

IV. SIMULATION AND EXPERIMENTAL RESULTS

In order to verify the feasibility of proposed converter and its performance, simulation and experimental results of odd-order HBC converter in as shown in Fig 12 are provided in this section. Here the simulation results are for the odd order HBC converter .A concern of the proposed converter is its input current spike due to the embedded switched capacitor stage. However a proper choice of switching frequency can mitigate the problem. The simulation results shows that the input spike can be suppressed by increasing the frequency due to the reduced voltage difference between two capacitors or capacitor and source.

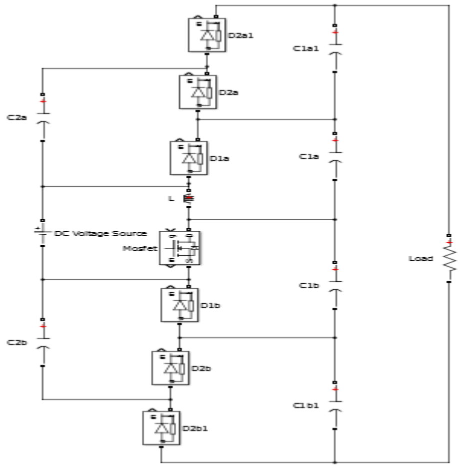
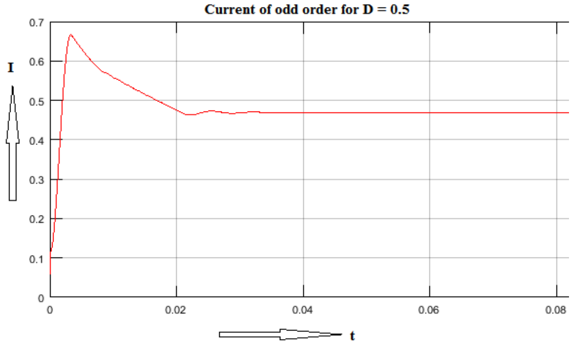
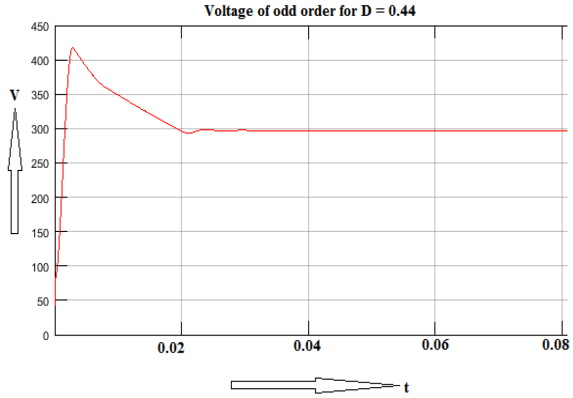
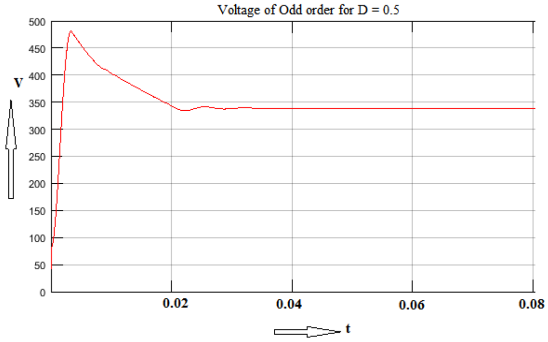


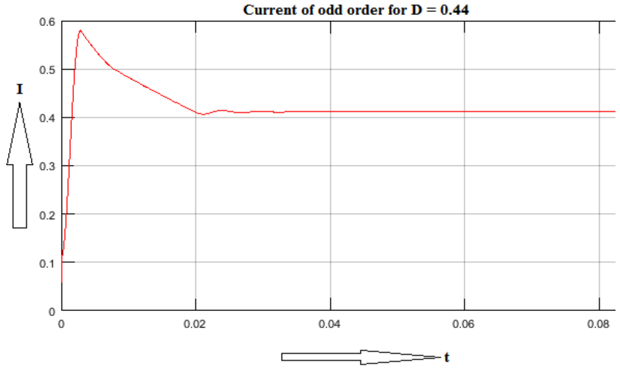
Fig 13. Simulation circuit of odd order HBC converter

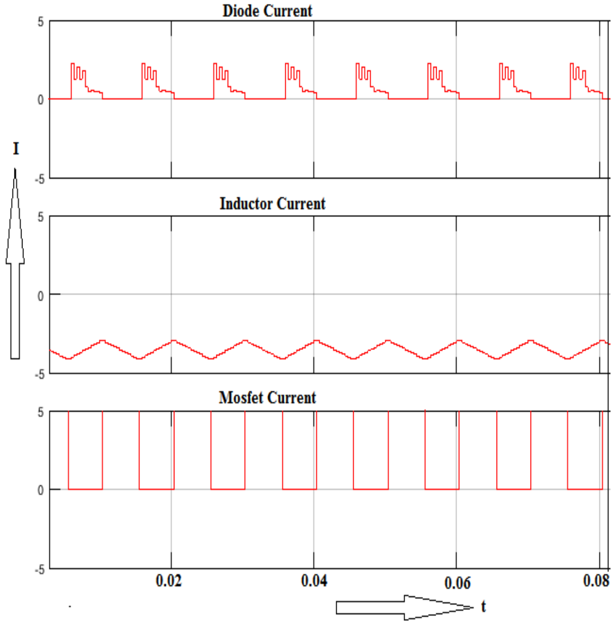
The simulation waveforms gives clear picture of output voltage (V_{out}),output current (I_{out}) as shown in the figure .As the odd order HBC converter topology is simulated the waveforms shows the overshoot at $V_{ds}$is observed and also by increasing the stages of BVM the voltage can be boosted to considerably high ratio compared even order .The waveforms gives a clear picture of the above said statement. The experimental output waveforms for different duty cycles is also verified.

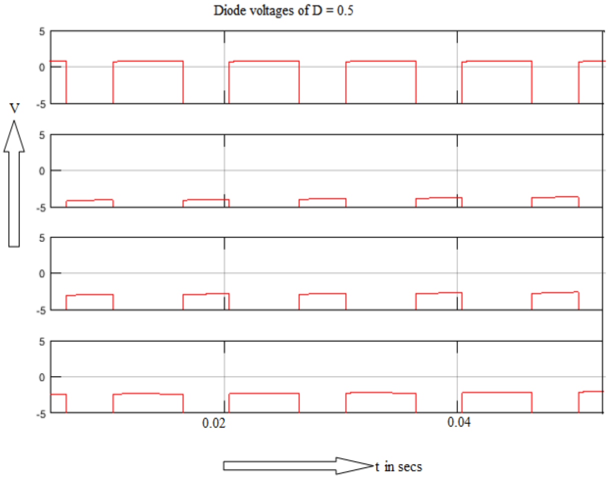

Current of odd order for D = 0.5


Voltage of odd order for D = 0.44


Voltage of Odd order for D = 0.5


Current of odd order for D = 0.44


Diode Current
Inductor Current
Mosfet Current


Diode voltages of D = 0.5

V. CONCLUSION

A new Hybrid Boosting Converter composed of an inductive switching core and Bipolar Voltage Multiplier is proposed in this paper. The proposed converter has the collective advantages of the gain boosting technique from voltage multiplier and voltage regulation capability from boost converter, featuring in nature interleaved operation, wide regulation range, low component stresses, small output ripple, flexible gain extension, and high efficiency. Compared with other high gain boosting technologies such as tapped inductor, multi-inductor/switch method or transformer based method, the proposed topology has reduced the complexity which is suitable for mass production. Compared with other single switch and single inductor DC-DC converters, it has a better component utilization rate, smaller output ripple and lower component stress. This paper provides operation principleand overall comparison with many other similar topologies. A 200W, 35V to 380V odd-order HBC issimulatedand its corresponding waveforms are obtained. This converter is suitable for many renewable energy applications such as the front-end for PV system.

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