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Transformerless DC/DC Converters for High Gain using Switched Inductor

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***Abstract*—Oil and electricity prices have been soaring as the supply of global energy is increasingly becoming deficient. The limited availability of energy sources have become an inevitable global problem. With global energy shortage, distributed energy sources such as photo-voltaic cells, fuel cells, wind energy, micro turbine generators, etc., are now widely promoted around the world. The renewable energy grid connected power system with photo-voltaic and fuel cells calls for high step-up and high efficiency DC/DC converters because the low voltage generated by these energy sources should be boosted to a high voltage for inverter to feed the AC utility. A transformerless DC - DC high step up switched inductor converters is used here, which combines the passive and active switched inductor unit , which has the advantages like high voltage conversion ratio, low voltage stress across the switches, low conduction loss on switches, and easy to control . Analysis and comparison of various switched inductor based converter is also done in this paper.**

***Index Terms*— High Step-Up DC/DC Converter; Switched Inductor; Switched Capacitor; Standalone.**

I. INTRODUCTION

Taking the cost and reliability issues into consideration, the voltage of the fuel cell stack is usually lower , it is required to be boosted to a high voltage typically 380 V DC for the DC/AC Inverter[21]. The traditional boost converter cannot meet this requirement, since to get the required voltage the converter need to be operated with duty ratio close to 1 and it induces high current ripple with low efficiency [21].
Various topologies have been developed to provide a high step-up without an extremely high duty ratio[21].The isolated converters which include the half bridge and full bridge types , can adjust the voltage ratio by increasing the turns ratio of the transformers [11]. As the transformer losses are a function of switching frequency, the maximum operating frequency is limited [13].This results in increased converter size making the converter bulky and expensive[13].If the industrial application does not require for DC isolation, the use of a transformer would only increase the cost, the volume, and the losses [7]. Non-isolated high step-up converters are employed to achieve high efficiency and low cost, and can be generalized as the coupled inductor type and non-coupled inductor type [21]. A number of coupled inductor based high step-up converters have been developed , by increasing the turns ratio of the coupled inductor, which is similar to that in isolated converters, high voltage gain can be achieved [21].
The conventional boost and buck-boost converters may be the simplest topologies [9]. However, they are

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limited in practical applications by the latch up condition and the degradation in the overall efficiency as the duty ratio D approaches unity [9]. Furthermore, the resulting voltage stress of the switches is high [9]. The extreme duty ratio not only induces very large current ripples but also increases conduction losses [9]. The extreme duty cycle may even cause malfunctions at high switching frequency due to the very short conduction time of the diode in step-up converters [7].

Various switched inductor and switched capacitor structures are present to extend the voltage gain [21]. By splitting the output capacitor of a basic boost converter, and combining the resulting capacitors with the main switch in the form of a switched capacitor circuit, a new step up structure is realized [4]. An output filter is added as usual in boost converters for getting a free ripple output [4]. Simple switched capacitor step-up structures showed that the dc gain depends on the number of capacitors of the switched capacitor circuit [3].

With the transition in series and parallel connection of the switched inductor, an inherent high voltage gain can be achieved [21]. The switched inductor based boost converter is then derived, but the voltage gain is still limited and hard to deal with high voltage ratio to meet the demands of the inverter; in addition, the switch voltage stress is also high [21]. Although more switched cells can be added to increase the voltage conversion ratio, the topology is very complex [21]. The modified boost type with switched inductor technique structure of converter is very simple [8]. Only one power stage is used in this converter [8]. However, this converter has two issues: 1) three power devices exist in the current flow path during the switch-on period, and two power devices exist in the current flow path during the switch-off period, and 2) the voltage stress on the active switch is equal to the output voltage [8].

II. Passive SwitchedInductor

Fig. 1 shows the circuit configuration of the Passive switched inductor , which consists of two inductors L_1, L_2 and three diodes D_1, D_2, D_3, when the switch is on, diodes D_1 and D_2 is forward biased and D_3 is reverse biased, two inductors are connected in parallel ; when switch is off ,diodes D_1 and D_2 are reverse biased and D_3 is forward biased, then the two inductors are series connected.

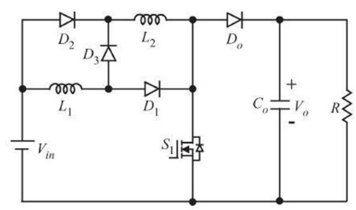

Fig. 1. Passive switched inductor [8]

A. Analysis of Passive Switched Inductor

The operating modes can be divided into two modes, defined as modes 1 and 2.

1) Mode1: During this time interval, switch S is turned on. The equivalent circuit is shown in Fig. 2. Inductors are charged in parallel from the DC source. Thus, the voltages across inductors are given as,

$$V_{L_1} = V_{L_2} = V_{in} \quad (1)$$

$$V_{D_3} = V_{in} \quad (2)$$

$$V_{D_0} = V_o \quad (3)$$

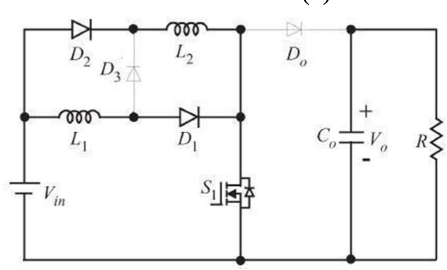

Fig. 2.Equivalent circuits of P-SL unit when switch is ON

2) Mode 2: During this time interval, switch S is turned off. The equivalent circuit is shown in Fig.3. The DC source and inductors are series connected to transfer the energies to C_o and the load. Voltage across inductors can be given as ,

$$V_{L_1} = V_{L_2} = \frac{V_{in} - V_o}{2} \quad (4)$$

$$V_{D_1} = V_{D_2} = \frac{V_o - V_{in}}{2} \quad (5)$$

$$V_S = V_o \quad (6)$$

Applying Volt-Sec balance,

$$V_{in} D T_s + \frac{V_{in} - V_o}{2}(1 - D)T_s = 0 \quad (7)$$

Voltage gain of CCM ,

$$G_{CCM} = \frac{V_o}{V_{in}} = \frac{1 + D}{1 - D} \quad (8)$$

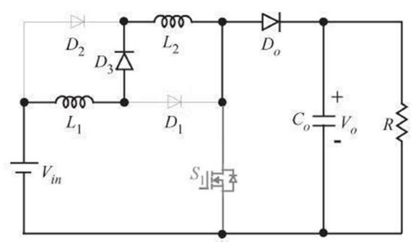

Fig. 3.Equivalent circuits of P-SLunit when switch is OFF

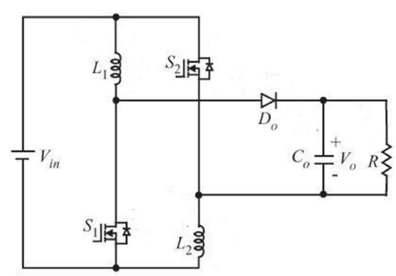

Fig. 4.Active switched inductor [8]

III. ACTIVE SWITCHED INDUCTOR

Fig. 4 shows the circuit configuration of the Active switched inductor, which consists of two inductors $L1$, $L2$ and two switches $S1$, $S2$; when the switches are on, two inductors are connected in parallel; when switches are off, and the two inductors are series connected.

A. Analysis of Active Switched Inductor

The operating modes can be divided into two modes, defined as modes 1 and 2.

1) Mode 1: During this time interval, switches are turned on. The equivalent circuit is shown in Fig. 5. Inductors are charged in parallel from the DC source. Thus, the voltages across inductors are given as,

$$V_{L1} = V_{L2} = V_{in} \quad (9)$$
$$V_{Do} = V_o \quad (10)$$

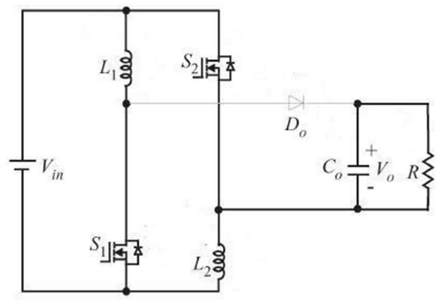

Fig. 5.Equivalent circuits of A-SL unit when switch is ON

2) Mode 2 : During this time interval, switches are turned off. The equivalent circuit is shown in Fig.6. The DC source and Inductors are series connected to transfer the energies to C_o and the load. Voltage across inductors can be given as,

$$V_{L_1} = V_{L_2} = \frac{V_{in} - V_o}{2} \quad (11)$$
$$V_{S_1} = V_{S_2} = \frac{V_{in} + V_o}{2} \quad (12)$$

Applying Volt-Sec balance,

$$V_{in} D T_s + \frac{V_{in} - V_o}{2}(1 - D)T_s = 0 \quad (13)$$

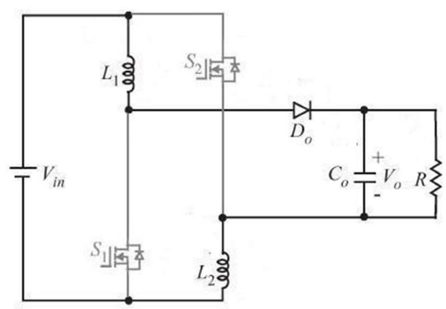

Fig. 6.Equivalent circuits of A-SLunit when switch is OFF

Voltage gain of CCM,

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

IV. HYBRID SWITCHEDINDUCTOR

A high voltage gain can be achieved by combining the P- SL and A-SL units. The inductors $L1$ and $L2$ in A-SL unit can be substituted with P-SL unit, then the proposed H-SLCs can be obtained, as shown in Fig. 7. The circuit c consists of four inductors $L1a$,$L1b$,$L2a$,$L2b$ and two switches $S1$, $S2$; when the switches are on, inductors are connected in parallel ; when switches are off , the inductors are series connected.

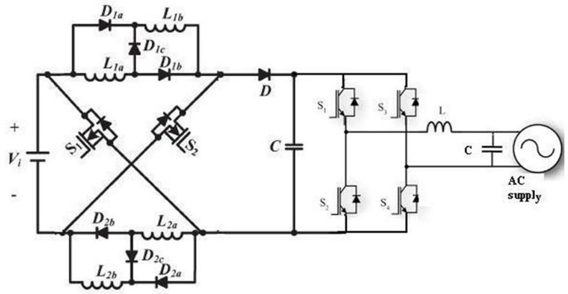

Fig. 7. Hybrid switched inductor for AC load

A. Analysis of Hybrid Switched Inductor

The operating modes can be divided into two modes, defined as modes 1 and 2. 1) Mode 1 :During this time interval, switches are turned on. The equivalent circuit is shown in Fig. 9 . Inductors are charged in parallel from the DC source.

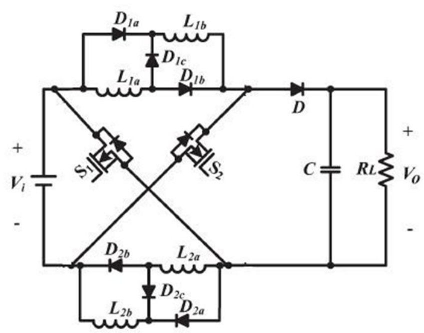

Fig. 8. Hybrid switched inductor [21]

Thus, the voltages across inductors are given as,

$$V_{L_{1a}} = V_{L_{2a}} = V_{L_{2b}} = V_{L_{1b}} = = V_{in} \tag{15}$$

$$V_{D_{2c}} = V_{D_{1c}} = V_{in} \tag{16}$$

$$V_D = V_o + V_{in} \tag{17}$$

2) Mode 2 : During this time interval, switch S is turned off. The equivalent circuit is shown in Fig.10. The DC source and inductors are series connected to transfer the energies to C and the load. Voltage across inductors can be given as,

$$V_{L_1} = V_{L_2} = \frac{V_{in} - V_o}{4} \tag{18}$$

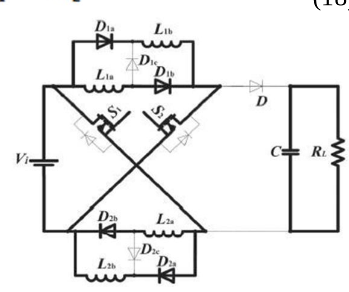

Fig. 9.Equivalent circuits of H-SL unit when switch is ON

$$V_{D_{1a}} = V_{D_{1b}} = V_{D_{2a}} = V_{D_{2b}} = \frac{V_{in}-V_o}{4} \quad (19)$$

$$V_{S_1} = V_{S_2} = \frac{V_{in}+V_o}{2} \quad (20)$$

Applying Volt-Sec balance,

$$V_{in}DT_s + \frac{V_{in}-V_o}{4}(1-D)T_s = 0 \quad (21)$$

Voltage gain of CCM ,

$$G_{ccm} = \frac{1+3D}{1-D} \quad (22)$$

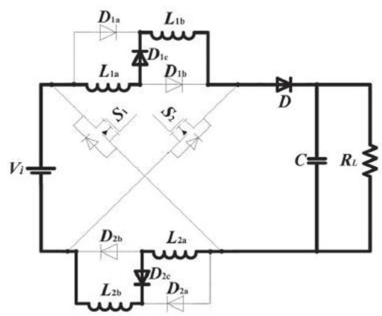

Fig. 10.Equivalent circuits of H-SLunit when switch is OFF

V. Comparison of Switched Inductor Converters and Boost Converter

The voltage stresses on the components (diode, switch) and the voltage gains of the converters are summarized in Table I. It can been seen that voltage stress on the active switch of the hybrid switched inductor and active switched inductor are less than that on the active switch of passive switched inductor and boost converter . Thus, the active switches with low voltage ratings and low ON-state resistance levels $R_{DS(ON)}$ can be selected. Moreover, the curves of the voltage gain of the boost converter and the switched inductor converters are shown Fig 11. As illustrated, the hybrid switched inductor converters can achieve high step-up voltage gain with low voltage stress.

TABLE I: Comparison of Switched Inductor Converters and Boost Converter

	H-SLC	A-SLC	P-SLC	B-C
Voltage gain	$\frac{1+3D}{1-D}$	$\frac{1+D}{1-D}$	$\frac{1+D}{1-D}$	$\frac{1}{1-D}$
Voltage of MOSFET	$\frac{V_{in}+V_o}{2}$	$\frac{V_{in}+V_o}{2}$	V_o	V_o
Voltage of D_o	$V_{in} + V_o$	$V_{in} + V_o$	V_o	V_o

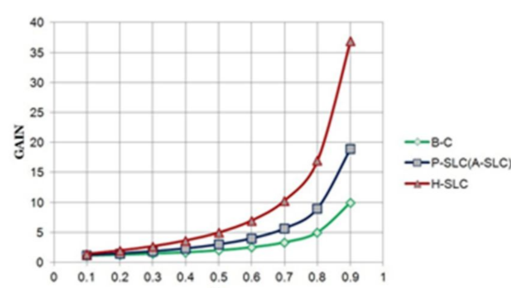

Fig. 11. Voltage gain versus duty ratio of B-C and the three SL-C

VI. SIMULATION RESULTS

Under the conditionsV_{in} = 40V, inductors = 500 μH; C_O= 470μF , converters are simulated using the MATLAB in open loop at a switching frequency of 50KHz , duty cycle=0.74. Figure 12 ,13 ,14 ,15 represent the simulation results of boost converter (B-C), passive switched inductor converter (P-SLC), Active switched inductor converter (A-SLC),Hybrid switched inductor converter (H-SLC) respectively. It can been seen that H-SLC has low voltage stress and high voltage gain compared with other converters , hence closed loop simulation of H-SLC is done and the obtained dc output is given to the inverter to get acsupply.

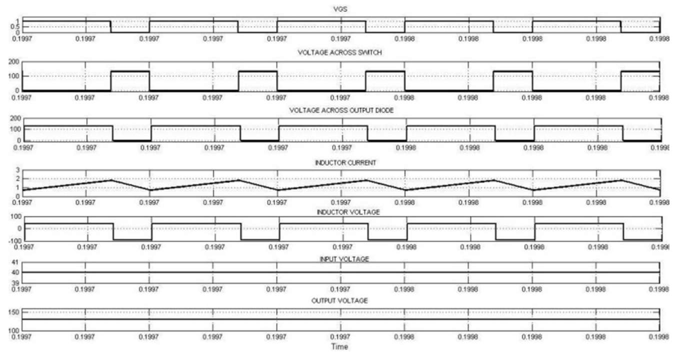

Fig. 12. Waveform of BC

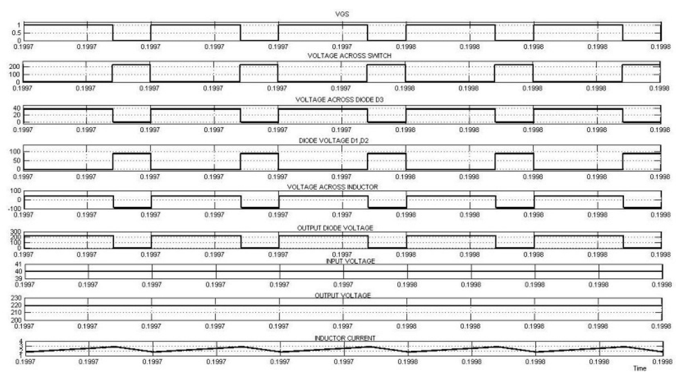

Fig. 13. Waveform of P-SLC

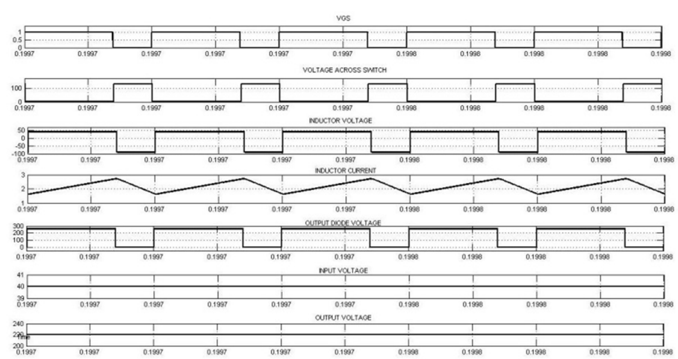

Fig. 14. Waveform of A-SLC

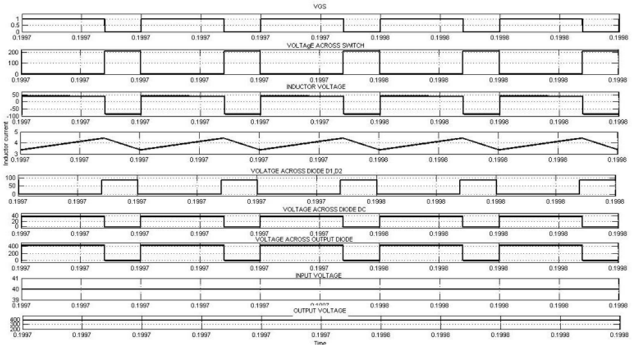

Fig. 15. Waveform of H-SLC

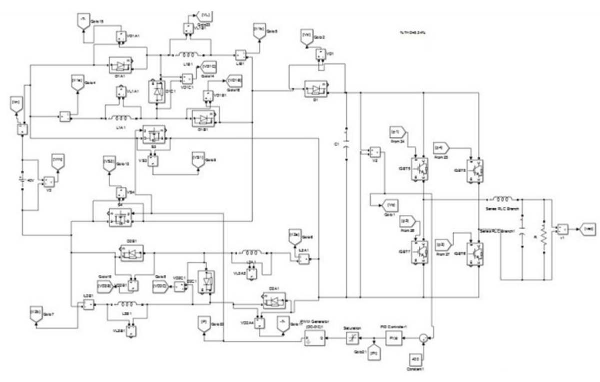

Fig. 16.Simulation Diagram

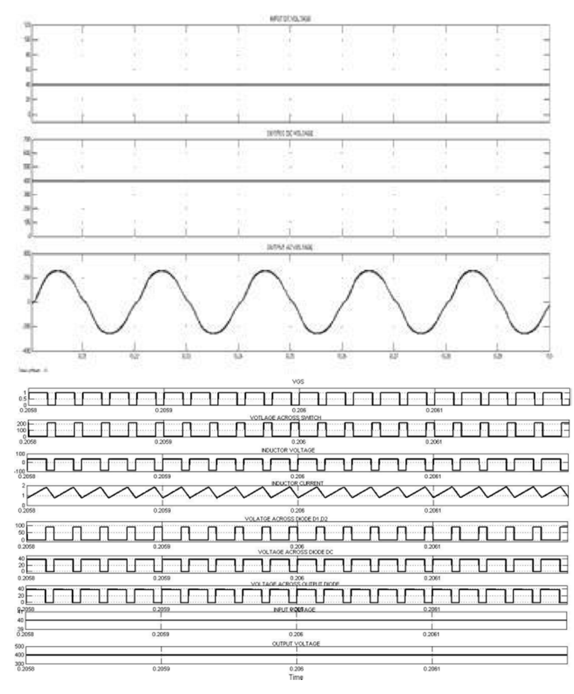

Fig. 17. Waveform (closed loop) of H-SLC

VII. CONCLUSION

The SLC has been designed and simulated using MATLAB software. Based on the results obtained it can be concluded that:

1. The H-SLC can achieve a high gain with a small duty cycle that is difficult for B-C, P-SLC, A-SLC converter.
2. The proposed H-SLC combines the advantages of a passive switched inductor, active switched inductor and boost converter which can bring down the voltage stress of switches

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