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NON-ISOLATED HIGH STEP-UP DC–DC CONVERTERS ADOPTING SWITCHED-CAPACITOR CELL

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ABSTRACT: In this concept, an isolated high step-up single switch DC-DC converter for renewable energy source is proposed. In the proposed converter high step-up voltage is obtained by single power switching technique that operates low duty cycle with isolated transformer inductors and switched capacitors and power diodes. The disadvantage of conventional converters is that it has high duty ratio and high voltage stress on power devices with less efficiency. The proposed converter eliminates the switching losses and recycles the leakage energy which includes reverse recovery energy of the power diode by using passive clamp circuit. To achieve high output voltage gain, the isolated transformer primary terminal and secondary terminal are connected in series during switching operation. The results are obtained through Matlab/ Simulink software package.

Key Words: High efficiency, high voltage gain, non-isolated, switched capacitor (SC).

I. INTRODUCTION

In recent years, the need and demand for electrical energy has increased due to the extensive use of electrical equipment and the technology development, and this trend is constantly growing. Consequently, researchers and governments worldwide have realized that the future relies on renewable energy due to the environmental concerns as the non-renewable energy sources are getting depleting [1], [2]. Among various renewable energy sources, the photovoltaic (PV) cell and fuel cell have been considered attractive choices [3]–[5]. However, without extra arrangements, the output voltages generated from both of them are with rather low level [6], [7]. A high step up dc-dc converter is used in the power conversion systems corresponding to these two energy sources for various applications [8]. DC–DC converter with a high step-up voltage gain is used for many applications, such as highintensity discharge lamp ballasts for automobile headlamps, fuel-cell energy conversion systems, solar-cell energy conversion systems, front-end stage for a battery source, and telecommunication industry and battery backup systems for uninterruptible power supplies [9]. Theoretically, a dc–dc boost converter can achieve a high step up voltage gain with an extremely high duty ratio. However, in practice, the step-up voltage gain is limited due to the effect of power switches, rectifier diodes, and the equivalent series resistance (ESR) of inductors and capacitors

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[10]. Moreover, the extremely high duty-ratio operation will result in a serious reverse-recovery problem. A dc–dc fly back converter is a very simple structure with a high step-up voltage gain and an electrical isolation, but the active switch of this converter will suffer a high voltage stress due to the leakage inductance of the transformer [11]. For recycling the energy of the leakage inductance and minimizing the voltage stress on the active switch, some energy-regeneration techniques have been proposed to clamp the voltage stress on the active switch and to recycle the leakage-inductance energy.All existing DC/DC converters were designed to meet the requirements of certain applications. They are called by their function, for example, buck converter, boost converter, buck boost converter, zero current switching converter, zero voltage switching converter [12-13]. The main features of DC – DC converters are High voltage gain without using extreme duty cycles or transformers, which allow high switching frequency and Low voltage stress in switching devices, along with modular structures and more output levels can be added without modifying the main circuit, which is highly desirable in some applications such as renewable energy systems [14]. Many applications require a DC–DC converter with high step up voltage gain, one of the most important applications is the green energy generation, where the low voltage from a renewable energy source need to be boosted for feeding a load or a grid connected inverter.

II. BASIC SC CONFIGURATIONS ADOPTING INDUCTOR ENERGY STORAGE CELL

Fig.1 shows the topology of a step-up SC converter. Whenswitches Q_1, Q_2, Q_4, Q_5, . . . , Q_{3n-2}, Q_{3n-1} conduct, and Q_3,Q_6, . . . , Q_{3n} are turned off, the input voltage source chargesthe SCs C_1, C_2, . . . , C_n in parallel. When Q_1, Q_2, Q_4, Q_5, . . . , Q_{3n-2}, Q_{3n-1} are turned off, and Q_3, Q_6, . . . , Q_{3n} conduct,C_1, C_2, . . . , C_n and the voltage source are connected in seriesto supply the load. Therefore, the output voltage is $(n + 1)$. V_g, where n is the number of the SCs, and Vg is the input voltage.It can be seen that it is effective to increase the voltage gainby charging the SCs in parallel and discharging in series.However, the output voltage of this step-up SC converter cannotbe regulated, and it varies with the input voltage.

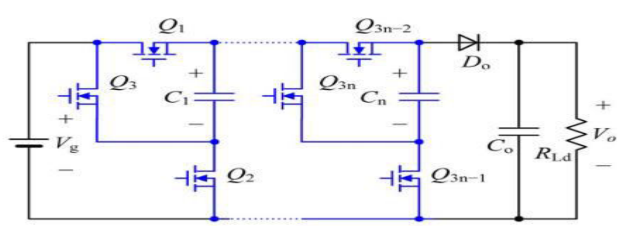
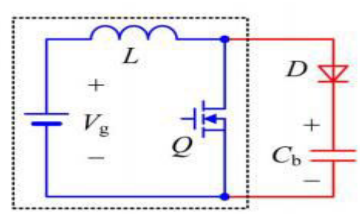
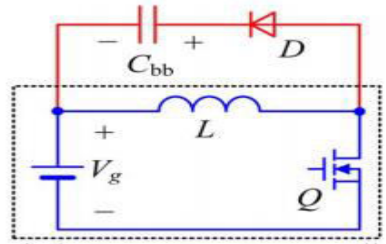


Fig.1 Step-up SC converter.



(a)Inductor energy storage cell



(b)Inductor energy storage cell

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Fig.2 SC structure with a single inductor energy storage cell.(a) Boost. (b) Buck–boost.To solve the problem, Fig.2 shows an inductor energystorage cell that is used to charge the SCs. When switch Q ison, the input voltage source charges the inductor. When Q isoff, the inductor charges the SC. The voltage of the SC can beregulated by adjusting the duty cycle of the switch.

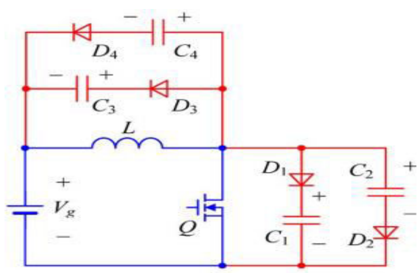


Fig.3 SC structure sharing an inductor energy storage cell.

The circuit shown in Fig.2(a) is similar to a boost converter,whereas the circuit shown in Fig.2(b) resembles a buck–boostconverter. Hereinafter, the SC is called the boost capacitorwhen it is in parallel with the switch, and the SC is called thebuck–boost capacitor when it is in parallel with the inductor.Diode D is used to prevent capacitor C from being shorted [see Fig.2(a)] or being in parallel with the input voltage source [see Fig.2(b)] when *Q* is on. Obviously, the positions of the diode and the SC can be exchanged.

At steady state, the volt–second relationship of the inductoris given as

$$V_g D_y T_s = (V_{Cb} - V_g)(1 - D_y)T_s = V_{Cbb}(1 - D_y)T_s \quad (1)$$

Where V_{Cb} and V_{Cbb} are the voltages of the boost capacitor andthe buck–boost capacitor, respectively, and Dy is the duty cycle. Then, V_{Cb} and V_{Cbb} can be derived as

$$V_{Cb} = \frac{V_g}{1 - D_y} \quad (2)$$

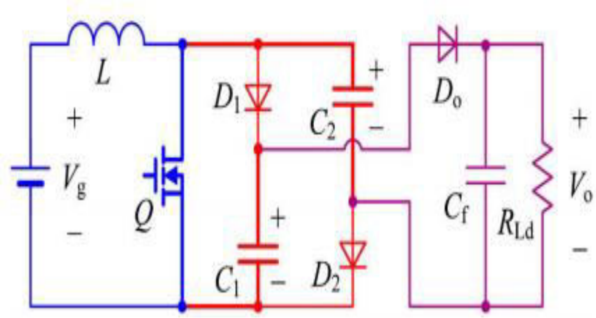
$$V_{Cbb} = \frac{D_y V_g}{1 - D_y} \quad (3)$$

Obviously, the voltage of the boost capacitor is higher than thatof the buck–boost capacitor with the same duty cycle.When the two SC structures shown in Fig.2 share theinductor energy storage cell and two position arrangements ofthe diode and capacitor, the SC structure sharing an inductorenergy storage cell can be derived as shown in Fig.3. Whenswitch *Q* is on, the input source charges the inductor. Whileswitch *Q* is off, C_1, C_2, C_3, and C_4 are simultaneously chargedby the inductor.

III. NONISOLATED HIGH STEP-UP DC–DC CONVERTER WITH SINGLE-INDUCTOR-ENERGY-STORAGECELL-BASED SCs (SIESC-SCs)

A. Derivation of High Step-Up Converter with SIESC-SCs

To obtain a high voltage gain, the SCs in Fig.3 should beconnected in series as many as possible when switch *Q* is on.Moreover, the polarities of the capacitors to be connected inseries should be different at the connection point. Since thepositive terminals of C_2 and C_4 are directly connected, C_2 andC_4 cannot be connected in series. Likewise, C_1 and C_3 cannotbe connected in series because the negative terminals of thetwo capacitors are connected through the input voltage source.



(a)

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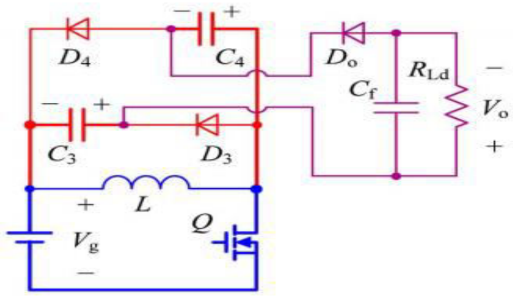
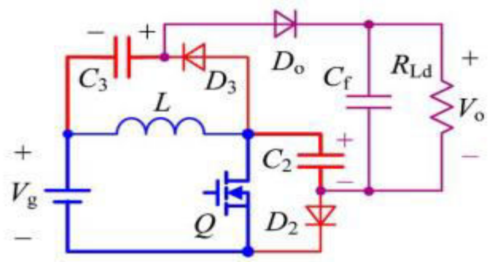
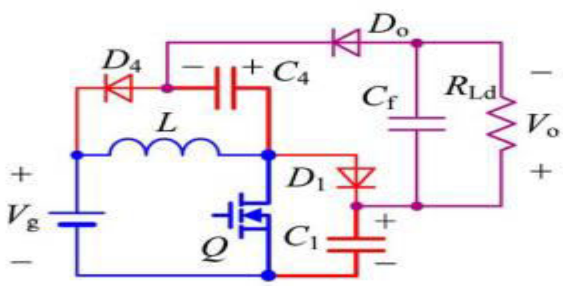


(b)



(c)



(d)

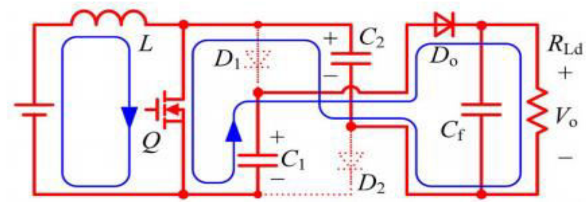
Fig.4. High step-up converters with SIESC-SCs derived from (a) boostconverter, (b) buck–boost converter, (c) Type-I boost/buck–boost-basedconverter, and (d) Type-II boost/buck–boost-based converter.

Therefore, only two of the four SCs can be connected in series in Fig.3. The possible connection methods of two SCs in series are shown in Fig.4, where the two SCs that can be connectedin series are shown with thick lines. C_1 and C_2 are connectedin series through switch Q as shown in Fig.4(a), C_3 and C_4 areconnected in series through Q as shown in Fig.4(b), C_2 and $C_3$are connected in series through Q as shown in Fig.4(c), and $C_1$and C_4 are connected in series through Q as shown in Fig.4(d).

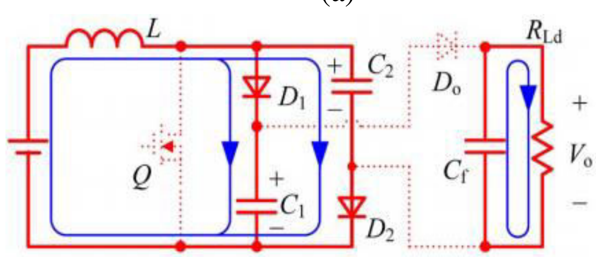
The series-connected capacitors are connected to the output filter capacitor C_f and load resistor R_{Ld} through diode Do.Noted that Do is used to prevent the output from being inparallel with one of the SCs when the power switch Q is turnedoff and the diodes conduct. The converters shown in Fig. 4(a)and (b) have been presented in [17].

B. Operating Principle

Referring to Fig.4(a), when the inductor current is continuous, there exist two operating modes for a high step-upconverter with SIESC-SCs derived from the boost converter.

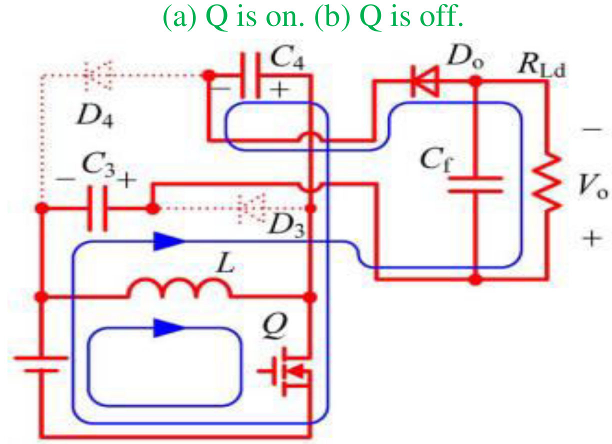


(a)



(b)

Fig.5. Operating modes of a high step-up converter with SIESC-SCsderived from boost. (a) Q is on. (b) Q is off.



(a)

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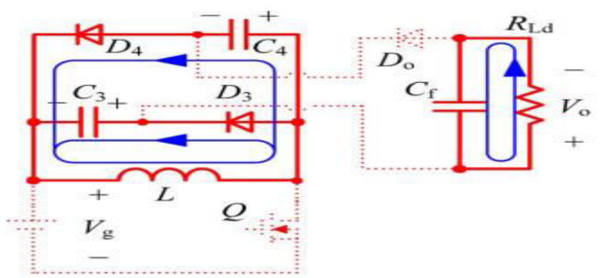


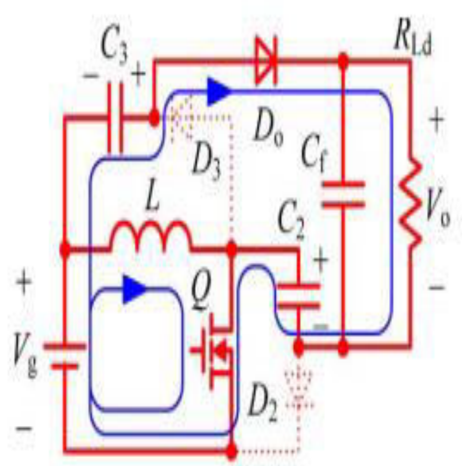
(b)

Fig.6. Operating modes of a high step-up converter with SIESC-SCs derived from buck–boost. (a) Q is on. (b) Q is off.

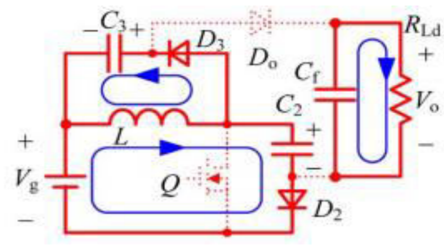
The topological equivalent circuits are shown in Fig.5. When$Q$is conducting, as shown in Fig.5(a), the input voltage sourcecharges the inductor. Meanwhile, C_2 is in series with C_1 tosupply the load through Q. When Q is turned off, as shown in Fig.5(b), the inductor charges C_1 and C_2 in parallel, and theload is powered by C_f. Since the two SCs in series when Q isconducting are both the boost capacitors, the voltage gain issource charges the inductor.

$$M = \frac{V_o}{V_g} = \frac{1}{1-D_y} + \frac{1}{1-D_y} = \frac{2}{1-D_y} \quad (4)$$

Similarly, the topological equivalent circuits for the other three converters in Fig.4 are shown in Figs.6–8, respectively. In Fig.6, when switch Q is turned on, the input voltage

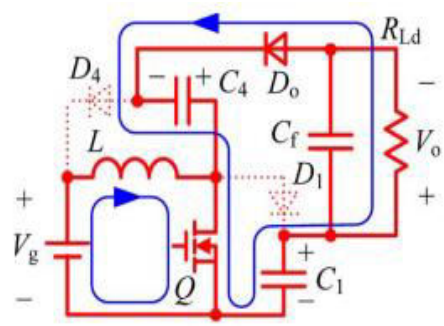


(a)

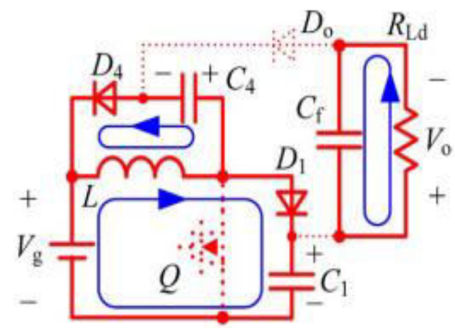


(b)

Fig.7. Operating modes of a high step-up converter with SIESC-SCsderived from Type-I boost/buck–boost-based converter. (a) Q is on.(b) Q is off.



(a)



(b)

Fig.8. Operating modes of a high step-up converter with SIESC-Scsderived from Type-II boost/buck–boost-based converter. (a) Q is on.(b) Q is off

Meanwhile, C_4 is in series withthe voltage source and C_3 to supply the load through Q. When$Q$ is turned off, the inductor charges C_3 and C_4 in parallel, andthe load is powered by C_f. In this converter, both the SCs arethe buck–boost capacitors and the two capacitors are in serieswith the voltage source to supply the load.

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Thus, the voltagegain of a high step-up converter with SIESC-SCs derived frombuck–boost converter is

$$M = \frac{V_o}{V_g} = \frac{D_y}{1 - D_y} + \frac{D_y}{1 - D_y} + 1 = \frac{1 + D_y}{1 - D_y}. \quad (5)$$

In Fig.7, when Q is turned on, the input voltage sourcecharges the inductor. Meanwhile, C_2 is in series with thevoltage source and C_3 to supply the load through Q. When $Q$is turned off, the inductor charges C_2 and C_3 simultaneously,and the load is powered by C_f. In this converter, one of theSCs is the boost capacitor, and the other one is the buck–boostcapacitor. The two capacitors and the voltage source are connected in series to supply the load. Thus, the voltage gain ofa high step-up converter with SIESC-SCs derived from Type-Iboost/buck–boost-based converter is

$$M = \frac{V_o}{V_g} = \frac{1}{1 - D_y} + \frac{D_y}{1 - D_y} + 1 = \frac{2}{1 - D_y} \quad (6)$$

In Fig.8, when Q is turned on, the input voltage sourcecharges the inductor. Meanwhile, C_4 is in series with C_1 tosupply the load through Q. When Q is off, the inductor chargesC_1 and C_4 simultaneously, and the load is powered by C_f. Inthis converter, one of the SCs is the boost capacitor, and theother one is the buck–boost capacitor. Therefore, the voltagegain of a high step-up converter with SIESC-SCs derived fromType-II boost/buck–boost-based converter is

$$M = \frac{V_o}{V_g} = \frac{1}{1 - D_y} + \frac{D_y}{1 - D_y} = \frac{1 + D_y}{1 - D_y} \quad (7)$$

C. Comparison of the Four Converters with SIESC-SCs

The features and voltage gains of the converters in Fig.4are listed in Table I, where M = Vo/Vg. Obviously, the voltagegains of the proposed converters are higher than that of the switching mode dc–dc converters with the same duty cycle. The two SCs in Fig.4(a) are both boost capacitors, and the voltagegain of this converter is relatively high. Although one SC is aboost capacitor and the other one is a buck–boost capacitor in Fig.4(c), the voltage gain of the converter is still as high as that of the converter in Fig.4(a) because of the inclusion ofthe input voltage source. The voltage gains of the converters shown in Fig.4(a) and (c) are higher than that of the converters shown in Fig.4(b) and (d). In the converter shown in Fig.4(a),the input voltage source cannot power the load directly. Theenergy from the input voltage source is first stored in the SCsand then released to the load by the SCs. In the converter shown in Fig.4(c), part of the energy is directly transferred to the loadfrom the input source when the switch conducts. Therefore, itcan be expected that the efficiency of the converter in Fig.4(c) is higher than that in Fig.4(a). Unfortunately, the input current of the converter shown in Fig.4(c) is pulsating.

IV. NONISOLATED HIGH STEP-UP DC–DC CONVERTER WITH MULTIPLE-INDUCTOR-ENERGY-STORAGECELL-BASED SCs (MIESC-SCs)

A. Derivation of High Step-Up Converter with MIESC-SCs

If the voltage gain needs to be increased further, based on the converters in Fig.4, more SCs can be added to be in serieswith existing SCs. Taking the converter shown in Fig.4(c) asan example, the SC C_3 is added as shown in Fig.9(a), and onemore inductor energy storage cell consisting of V_{g2}, Q_2, and $L_2$is added to replenish energy for C_3. When Q_1 and Q_2

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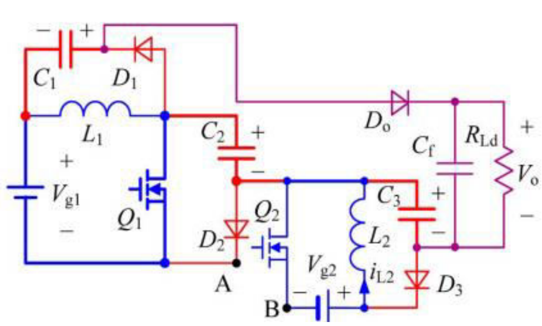
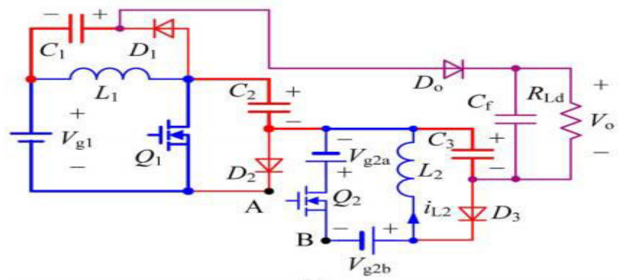
simultaneously conduct, V_{g1} charges L_1 through Q_1, and V_{g2} chargesL_2 through Q_2. C_1, C_2, C_3, and the input voltage source V_{g1} arein series to supply the load, as shown by thick lines in Fig.9(a).When Q_1 and Q_2 are turned off simultaneously, L_1 charges $C_1$and C_2 via D_1 and D_2, respectively, and L_2 charges C_3 via D_3.As Q_1 and Q_2 are turned on and off synchronously, $Q_1$and Q_2 are expected to share one switch for simplification.Thus, the voltage source V_{g2} is separated into two sourcesV_{g2a} and V_{g2b}, as shown in Fig.9(b). By connecting points Aand B, the branch consisting of C_2 and Q_1 is in parallelwith the branch consisting of V_{g2a} and Q_2. Thus, V_{g2a} canbe substituted by C_2, and Q_2 can be replaced by Q_1, andthe branch consisting of V_{g2a} and Q_2 can be removed. Then,a high step-up converter with double-inductor-energy-storagecell-based SCs derived from Type-I boost/buck–boost-basedconverter is obtained as shown in Fig.10, where the voltagesource V_{g2b} is formed with C_b. When Q is on, C_2 and C_b are connected in series to charge L_2, and C_1, C_2, C_3, and V_g are inseries to power the load. When Q is turned off, the current ofL_1 charges C_1 and C_2, whereas the current of L_2 charges C_3.As D_2 and D_3 conduct at the same time, the voltages of C_b andC_3 are equal. Similarly, a high step-up converter with MIESCSCs derived from Type-I boost/buck–boost-based converter is obtained as shown in Fig.11 by adding multiple SCs.

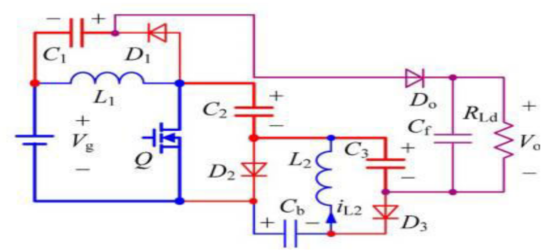


(a)



(b)

Fig.9. Extension of a high step-up converter with SIESC-SCs derived from Type-I boost/buck boost-based converter. (a) Adding onemore inductor-energy-storage-cell-based SC. (b) Separating the voltagesource Vg2 into two.



(c)

Fig.10. High step-up converter with double-inductor-energy-storagecell-based SCs derived from Type-I boost/buck–boost-based converter.

Likewise, based on the converters as shown in Fig.4(a), (b),and (d), high step-up dc–dc converters with MIESC-SCs are derived as shown in Fig.12.

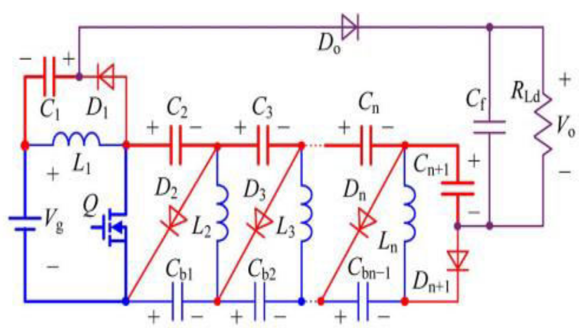


Fig.11. High step-up converter with MIESC-SCs derived from Type-I Boost/Buck–Boost-based converter.

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B. Operating Principle

The operating principles of high step-up converters withMIESC-SCs are similar. Here, the high step-up converterwith double inductor energy storage cells derived from Type-Iboost/buck–boost-based converter as shown in Fig.10 is takenas an example to analyze the operating mode. When the inductor current is continuous, there are three operating modes for theconverter. Fig.13 shows the key waveforms of the converter, where v_{gs} is the driving signal of the switch; V_{cb} and V_{c3} are the voltages of C_b and C_3, respectively; and i_{L1} and i_{L2} arethe currents of L_1 and L_2. The operating modes are shown in Fig.14. During $[t_0, t_1]$, switch Q is conducting, and theinput voltage source charges L_1, and C_2 charges C_b and L_2.Meanwhile, C_3 and C_2 are in series with the voltage source andC_1 to supply the load through Q. Thus, V_{c3} decreases whileV_{Cb} increases. As the voltages of C_b and C_3 are equal beforethe switch conducts, we have $V_{Cb} > V_{C3}$. During $[t_1, t_2]$, theswitch is turned off. Because $V_{Cb} > V_{C3}$, D_3 conducts andD_2 is remaining off. L_1 charges C_1 via D_1, and it chargesC_2 and C_3 and discharges C_b. Meanwhile, L_2 charges C_3 viaD_3. When V_{C3} increases to V_{Cb}, D_2 conducts, and L_2 chargesC_3 and C_b in parallel. Thus, $V_{C3} = V_{Cb}$. At the same time, $L1$charges $C1$ through $D1$ and charges C_2 through D_2.

At steady state, according to the volt–second relationships ofL_1 and L_2, we have

$$V_g D_y T_s = (V_{C2} - V_g)(1 - D_y)T_s$$

$$= V_{C1}(1 - D_y)T_s \quad (8)$$

$$(V_{C2} - V_{Cb})D_y T_s = V_{C3}(1 - D_y)T_s \quad (9)$$

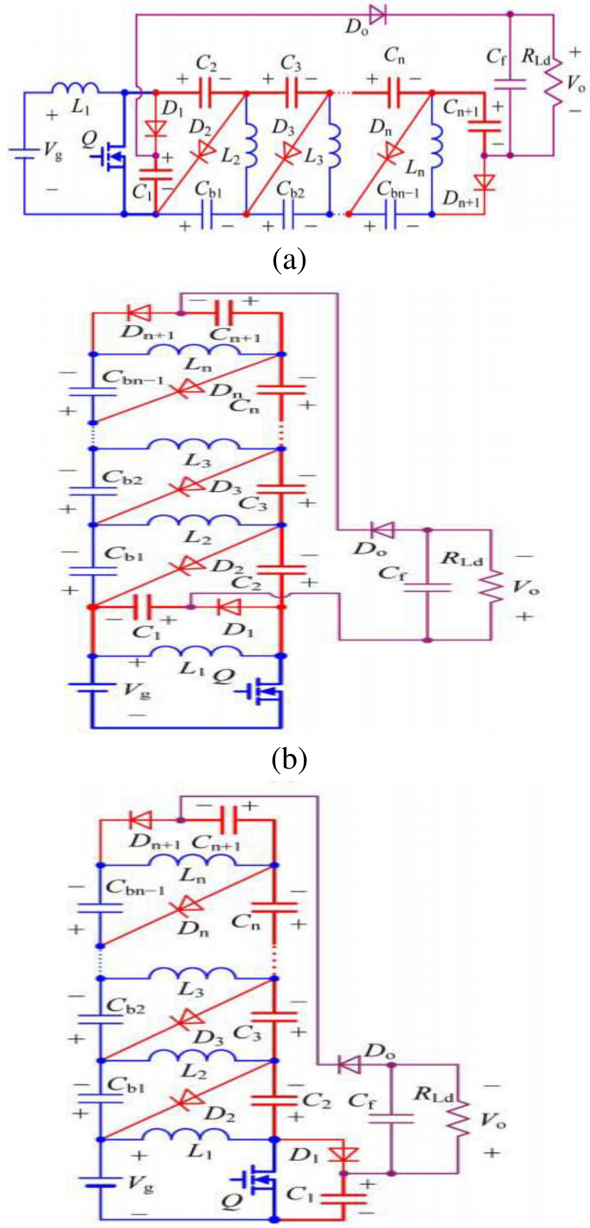


Fig.12. High step-up converters with MIESC-SCs derived from(a) boost converter, (b) buck–boost converter, and (c) Type-II boost/buck–boost-based converter.

Then,

$$V_{C2} = \frac{V_g}{1 - D_y} \quad (10)$$

$$V_{C1} = V_{C3} = V_{Cb} = \frac{D_y V_g}{1 - D_y} \quad (11)$$

When Q is on, C_3, C_2, and C_1 are in series with the voltagesource to supply the load. Therefore, the voltage gain of the

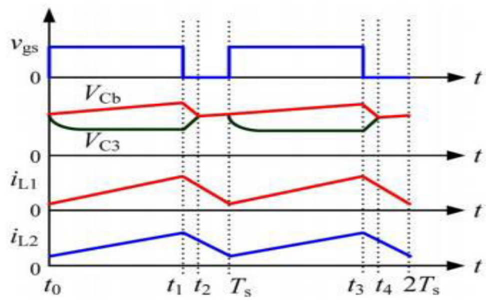
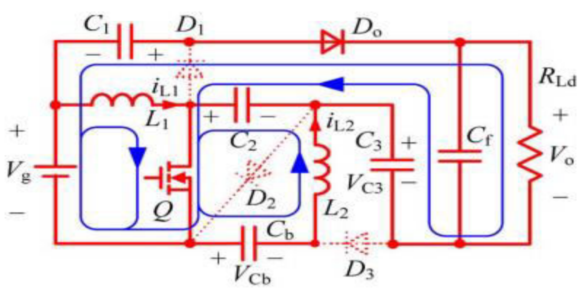
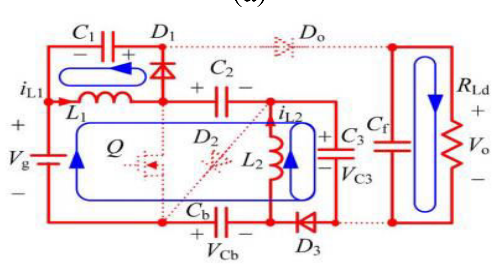


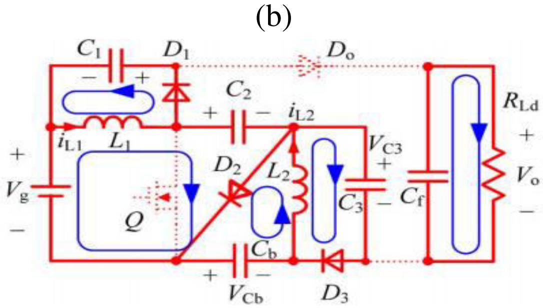
Fig.13. Key waveforms of high step-up converter with double inductorenergy storage cells based SCs derived from Type-I boost/buck–boostbased converter.



(a)



(b)



(c)

Fig.14. Operating modes of a high step-up converter with doubleinductor-energy-storage-cell-based SCs derived from Type-I boost/buck–boost-based converter. (a) $[t_0,t_1]$. (b) $[t_1,t_2]$. (c) $[t_2,T_s]$.

Converter can be derived as

$$M = \frac{V_o}{V_g} = \frac{V_{C3} + V_{C2} + V_{C1} + V_g}{V_g} = \frac{2 + D_y}{1 - D_y} \tag{12}$$

C. Voltage Gains of High Step-Up Converters with MIESC-SCs

Similar to the derivation of the voltage gain of a high stepup converter with double-inductor-energy-storage-cell-basedSCs derived from Type-I boost/buck–boost-based converter,the voltage gains of the other high step-up converters withMIESC-SCs can be derived, whereM = Vo/Vg, and n is the number of the inductors.As illustrated above, the high step-up converters withMIESC-SCs are derived from those with SIESC-SCs byadding more SCs. If the number of the inductors is n, thenumber of the added SCs is $n - 1$. The voltage of each added SC is $V_g D_y /(1 - D_y)$; thus, the voltage gains ofhigh step-up converters with MIESC-SCs are increased by$(n - 1)D_y/(1 - D_y)$.

V. MATLAB/SIMULINK RESULTS

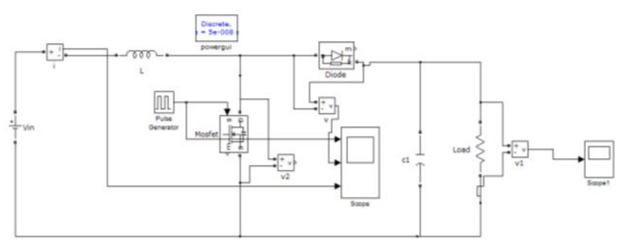
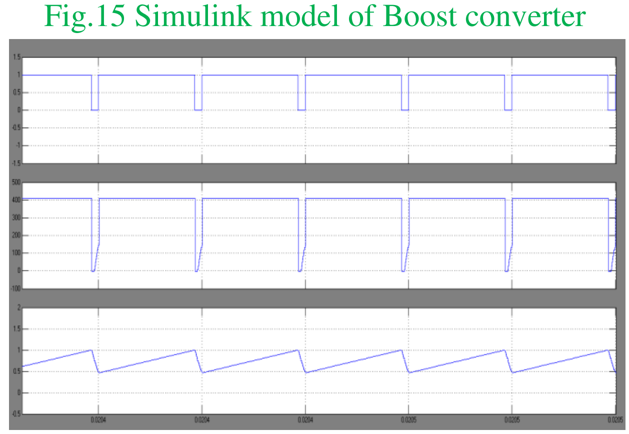


Fig.15 Simulink model of Boost converter



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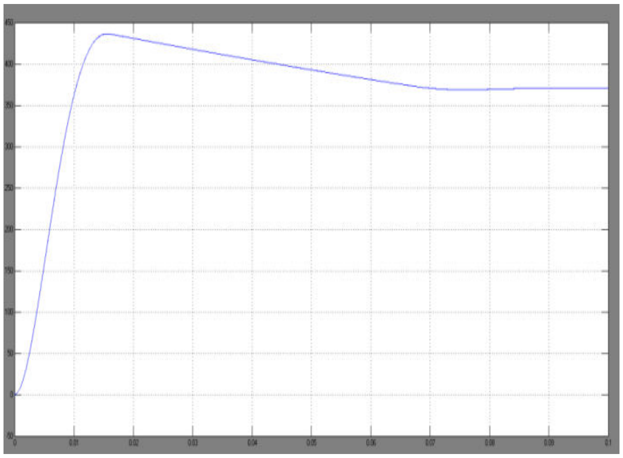
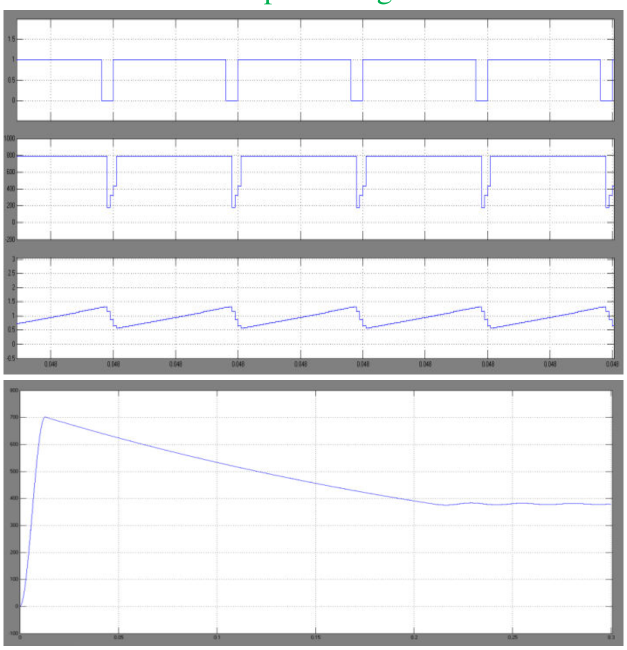
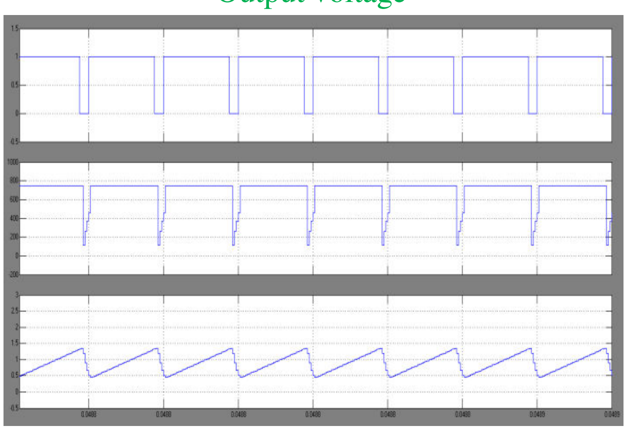
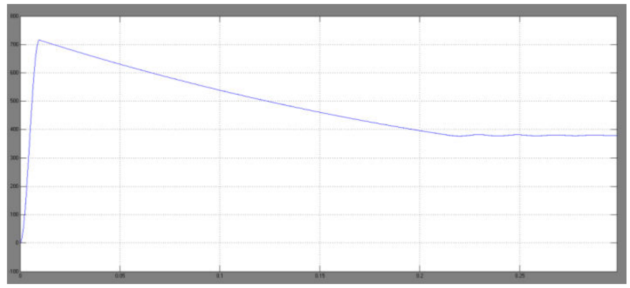


(a) Pulsing signals, Diode voltage, Current, Output voltage



(b) Pulsing signals, Diode voltage, Current, Output voltage





(c) Pulsing signals, Diode voltage, Current, Output voltage

Fig.16 Waveforms of boost converter (a)Vg=25V. (b)Vg=36V. (c)Vg=45V.

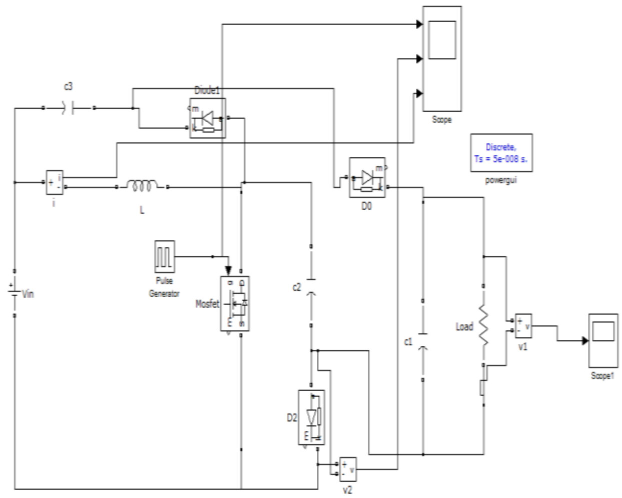
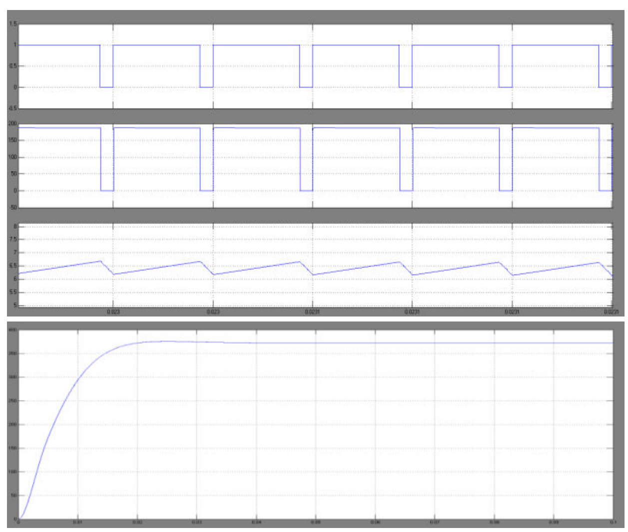


Fig.17 Simulink model of high step-up converterwith SIESC-SCs



(a) Pulsing signals, Diode voltage, Current, Output voltage

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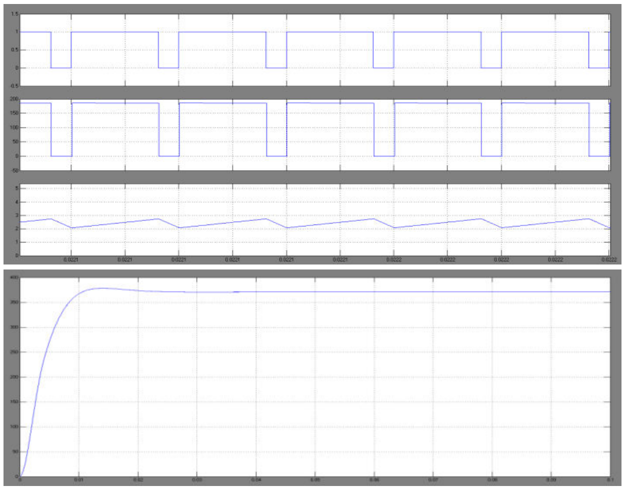
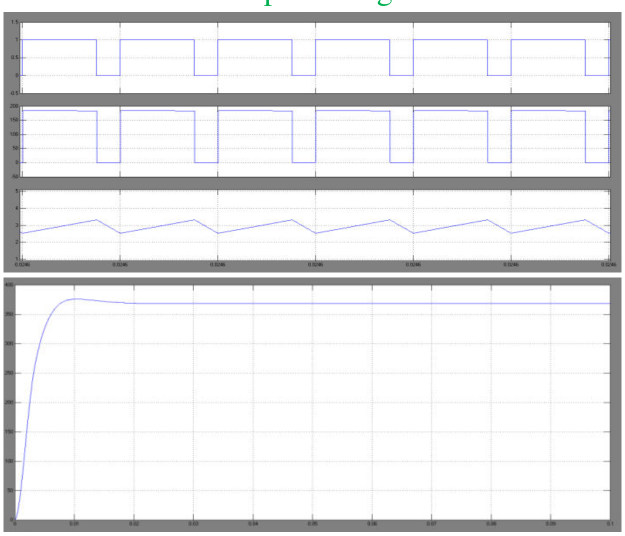


(b) Pulsing signals, Diode voltage, Current, Output voltage



(c) Pulsing signals, Diode voltage, Current, Output voltage

Fig.18Waveforms of high step-up converterwith SIESC-SCs(a)Vg=25V. (b)Vg=36V. (c)Vg=45V.

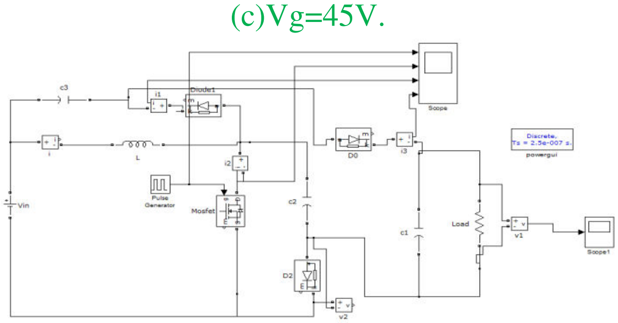
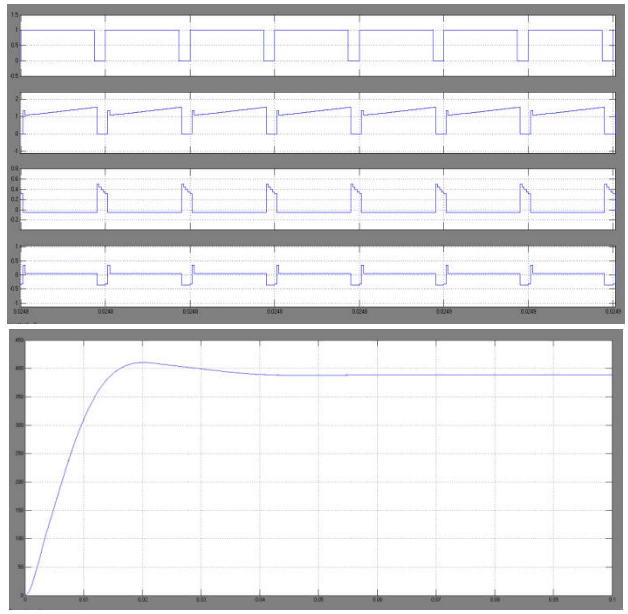
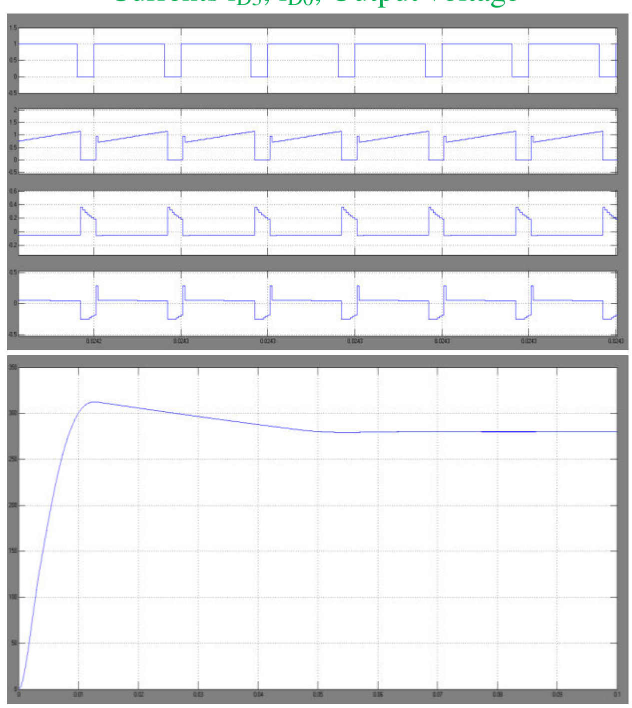


Fig.19 high step-up converter withSIESC-SCs derived from Type-I boost/buck–boost-based converter



(a) Pulsing signals, Switch Current (i_Q), Diode Currents i_{D3}, i_{D0}, Output voltage



(b) Pulsing signals, Switch Current (i_Q), Diode Currents i_{D3}, i_{D0}, Output voltage

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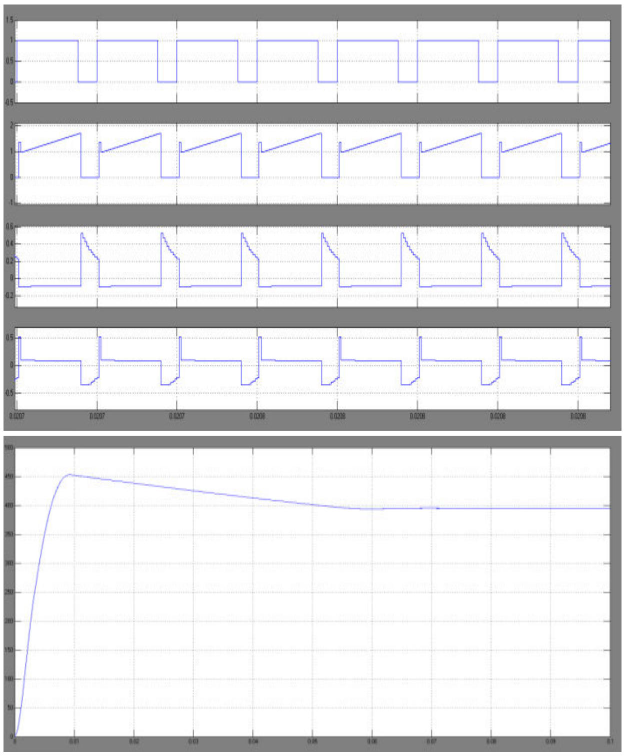


(c) Pulsing signals, Switch Current (i_Q), Diode Currents i_{D3}, i_{D0}, Output voltage

Fig.20 Waveforms of the high step-up converter withSIESC-SCs derived from Type-I boost/buck–boost-based converter. (a) Vg=25V. (b)Vg=36V. (c)Vg=45V.

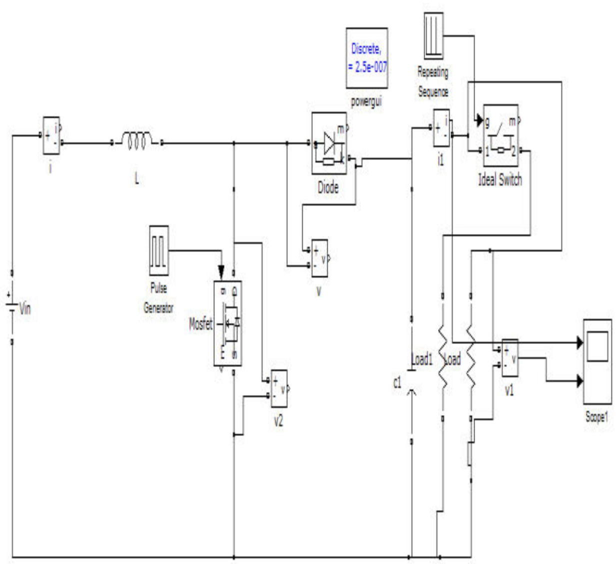
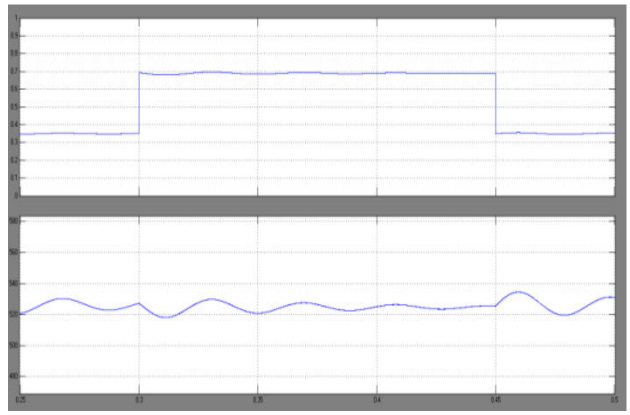
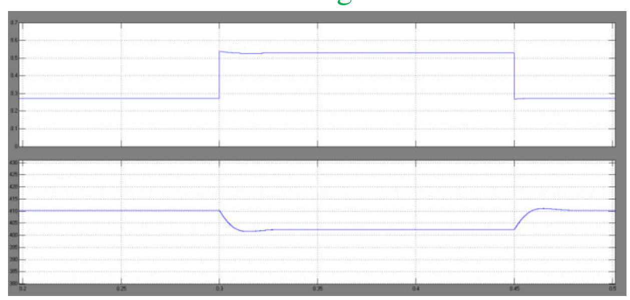


Fig.21 Boost converter with load current is step changed between full load and half load.



(a) Boost Converter Load Current and Output Voltage



(b) High step-up converter with SIESC-SCs Load Current and Output Voltage

Fig. 22 Load transient experiment waveforms when the load current is step changed between full load and half load. (a) Boost converter. (b) High step-up converter with SIESC-SCs derived from Type-Iboost/buck–boost-based converter.

VI. CONCLUSION

The High step up Switched Capacitor dc-dc converter is proposed in this paper. Thus a new method of combination of the SC converter and switching-mode dc–dc converter has been proposed. The output voltage and the efficiency of the proposed system is high. By using the Multiple Inductor Energy Storage Cell-SCs in the boost and buck-boost converters the output voltage and efficiency is improved. The results indicate that the converters proposed in this paper can steadily operate and that the performance is good.

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