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CLOSED LOOP OPERATION OF HIGH BOOST DC-DC CONVERTER OPERATING IN CCM MODE

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Abstract

A new boost converter with high voltage gain is proposed on this work. This converter is suitable for the applications with a high voltage gain between the input and the output. The proposed converter combines the concept of switched-capacitor and coupled-inductor techniques. The switched-capacitor technique proposed that capacitors can be parallel charged and series discharged to achieve a high step-up gain. This converter allows the utilization of MOSFET switch with lower conduction resistances RDS(On). It integrates a switched-capacitor (SC) circuit within a boost converter. The active clamp is connected in parallel with the primary side of the isolation transformer to recycle the energy stored in the leakage inductor of isolated transformer and to limit the peak voltage stress of switching devices due to the transformer leakage inductor when the main switch is turned off. In order to verify the feasibility of 200 W, 24 V DC input, 450 V DC output, Fsw=50 kHz topology; principle of operation, theoretical analysis, and closed loop operation, reference and line regulations and waveforms are shown.

Keywords: *Coupled inductor, Switched capacitor(SC), High boost, Active clamp.*

1. Introduction

Reliability becomes more important to power supplies for industrial applications. So, power supplies have adopted a battery back-up system in several applications. In addition to that, renewable energy such as the fuel cell is a hot issue in the research field. The common power supply for the above applications is a high boost converter to step up the low input voltage to high output voltage .[1].

DC–DC converter with a high step-up voltage gain is used for many applications, such as high-intensity discharge lamp ballasts for automobile headlamps, fuel-cell energy conversion systems, solar-cell energy conversion systems, front-end stage for a battery source, tele-communication industry and battery backup systems for uninterruptible power supplies. 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. Moreover, the extremely high duty-ratio operation will result in a serious reverse-recovery problem. A dc–dc flyback 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. 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. The coupled-inductor techniques provide solutions to achieve a high voltage gain, a low voltage stress on the active switch, and a high efficiency without the penalty of high duty ratio[2]-[3].

In this proposed system, the leakage energy of the coupled inductor is another problem as the main switch was turned OFF. It will result in a high-voltage ripple across the main switch due to the resonant phenomenon induced by the leakage current. In order to protect the switch devices, either a high-voltage-rated device with higher RDS(ON)or a snubber circuit is usually adopted to deplete the leakage energy. Here the magnetic core can be regarded as a flyback converter and most of the energy was stored in the magnetic inductor. However, the capacity of the magnetic core should be increased substantially when the demand of high output power required[4]. The dc-to-dc converters comprising high-frequency transformers can provide a high voltage gain, but their efficiency is drastically degraded by losses associated with the leakage inductors, which induce high voltage stress, large switching losses and serious electromagntic interference (EMI) problems[4].

Traditionally, the DCM of operation has been in favor, mainly due to its better dynamic behavior.Continuous conduction mode (CCM) of operation has become more attractive, since it leads to higher harmonic regulation and lower power losses[5]. The main drawback of snubbers, in general, is that their effectiveness depends strongly on line and load variations. There are two major concerns related to the efficiency of a high step-up dc–dc converter: large input current and high output voltage. The large input current results from low input voltage; therefore, low-voltage-rated devices with low RDS(ON)are necessary in order to reduce the conduction loss. Another concern is the severe reverse-recovery problem that occurs in the output rectifier due to the high output voltage. The boost and buck–boost converters are the simplest non-isolation topologies. Unfortunately, the switch sustaining the high output voltage has a high RDS(ON)[6].

2. Switched Capacitor and Active Clamp Circuitry

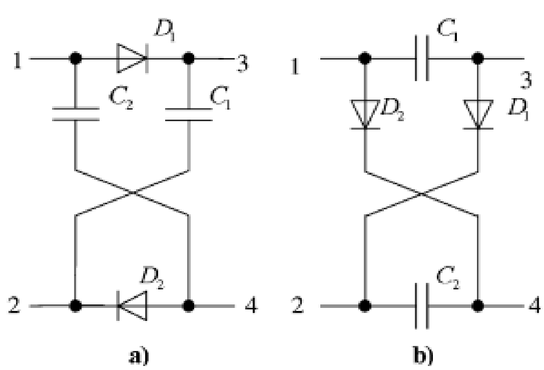

Fig.1. Step-up basic switching structure

The switched-capacitor technique is that the capacitors can be parallel charged and series discharged to achieve a high step up gain Fig.1 shows the switching topology for step up structures. The two capacitors C_1 and C_2 are charged in parallel during topology T_{off} and discharged series during topology T_{on}[7].

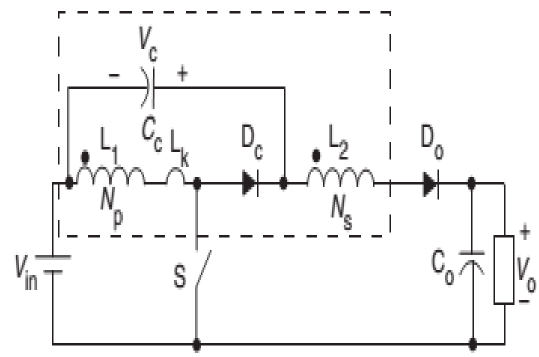

Fig.2. Clamp mode coupled inductor boost converter

Figure 2 shows a clamp mode boost converter, utilizing a coupled inductor to provide high step-up voltage gain to meet the requirements of many emerging applications, such as the high intensity discharge lamp (HID) ballast for automobiles and high step-up DC/DC converters. A snubber circuit employs the diode D_C, and capacitor C_C, and recycles the leakage energy of the coupled inductor[8]

The active-clamp flyback converter can recover the leakage energy and minimize the voltage stress. The drawbacks of the active-clamp solution are the topology complexity and the loss related to the clamp circuit

The current through the active clamp switch is the high primary current, which can induce high conduction losses in the active-clamp circuit. Taking advantage of the non-isolation requirement, the proposed solution shown in Fig.3 requires only one additional clamp capacitor and one diode . The converter can achieve a level of operation comparable to that of the active-clamp scheme. The clamp capacitor and the added diode function as the active-clamp charging path [9].

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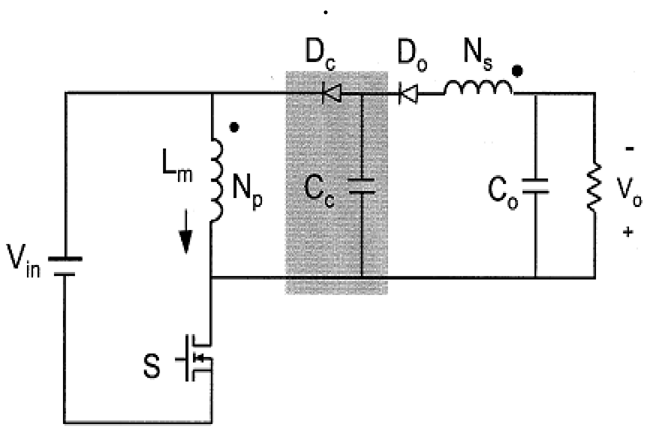


Fig.3 Proposed clamp-mode coupled-inductor buck–boost converter

3. High Boost DC-DC Converter

Conventional Dc-Dc converters are designed in the medium frequency range. The various types of converter are buck converter, boost converter, inverting and non-inverting buck-boost converter, cuk-converter, SEPIC converter, full-bridge and half-bridge converter, forward converter, push-pull converter, flyback converter, resonant converter, bidirectional converter and so on. These converters can be classified based on various categories. These converters can be classified as isolated and non-isolated converters, unidirectional and bidirectional converters, step-up and step-down converters, single input and multi-input converters, Low power application and high power application converters etc. The world is now habituated with the electronics devices without which it is very di cult for the mankind to keep going. So it is very important to develop the devices error free and fast response with high efficiency. Of the research field is dcdc converters. The dc-dc converters means the input is dc and the output is also dc. The two basic dc-dc converters are buck converter and boost converter. Based on these two converters, all other converters are derived. The semiconductor devices are used as switching devices due to which the converters can operate at high frequencies. The different arrangement of inductors and capacitors in th converters operates as a filter circuit. The resistance act as a load in the circuit which can be varied to study the behavior during light load and heavy load [10]

4. Circuit Operation and Analysis Of High Boost DC-DC Converter in CCM Mode

Fig. 4 shows the circuit topology of the high boost dc-dc converter. which is composed of dc input voltage V_{in}, main switch S, coupled inductors N_p and N_s, one clamp diode D_1, clamp capacitorC_1, two capacitors C_2 and C_3, two diodes D_2 and D_3, output diode D_o, and output capacitor C_o. The equivalent circuit model of the coupled inductor includes magnetizing inductor L_m, leakage inductor L_k, and an ideal transformer. The leakage inductor energy of the coupled inductor is recycled to capacitor C_1, and thus, the voltage across the switch Scan be clamped. The voltage stress on the switch is reduced significantly. Thus, low conducting resistance RDS(ON)of the switch can be used..

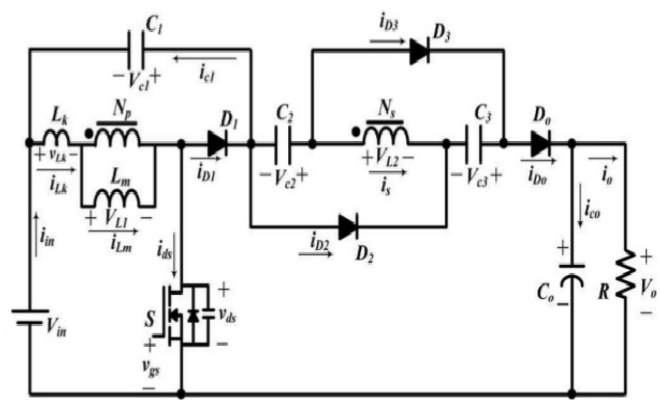


Fig.4.High Step Up Dc-Dc Converter

The concept is to utilize two capacitors and one coupled inductor. The two capacitors are charged in parallel during thetopology T_{off} period and are discharged in series during the topology T_{on} by the energy stored in the coupled inductor to achieve a high step-up voltage gain. Based on the topology, the proposed converter combines the concept of switched-capacitor and coupled-inductor techniques ie, two capacitors can be parallel charged and series discharged to achieve a high step-up gain. Thus, capacitors C2 and C3are charged in parallel and are discharged in series by the secondary side of the coupled inductor when the switch is turned off and turned on. Because the voltage across the capacitors can be adjusted by the turn ratio, the high step-up gain can be achieved significantly. Moreover, the secondary-side leakage inductor of the coupled inductor can alleviate the reverse-recovery problem of diodes, and the loss can be reduced. In addition, the proposed converter adds capacitors C2 and C3 to achieve a high step-up gain without an additional winding stage of the coupled inductor. Fig.5 shows the waveforms of the high boost dc-dc converter in CCM mode.

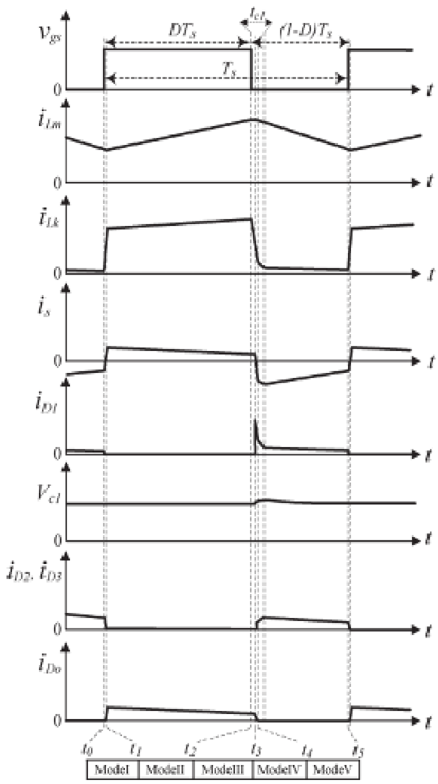


Fig.5. Waveforms in CCM

The main operating principle is that, when the switch is turned on, the coupled-inductor-induced voltage on the secondary side and magnetic inductor Lm is charged by Vin. The induced voltage makes Vin, VC1, VC2, and VC3 release energy to the output in series. The coupled inductor is used as a transformer in the forward converter. When the switch is turned off, the energy of magnetic inductor Lm is released via the secondary side of the coupled inductor to charge capacitors C2 and C3 in parallel. The coupled inductor is used as a transformer in the flyback converter.

5. Modes of Operations in CCM

The proposed converter operating in continuous conduction Mode is explained.

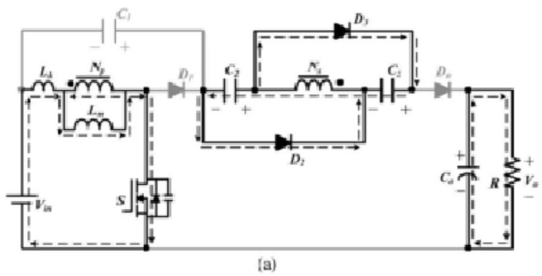


Fig.6. Mode I

Mode I [t0,t1]: switch S is turned on. Diodes D_1 and Do are turned off, and D_2 and D_3 areturned on. According to KVL $V_{in} = V_{Lk}+V_{Lm}$. The leakage inductor L_k starts to charge by Vin. Due $L_{k,}$ the secondary-side current is of the coupled inductor is decreased linearly. Output capacitor Co provides its energy to load R. When current iD2 becomes zero at t=t1 this operating mode ends.

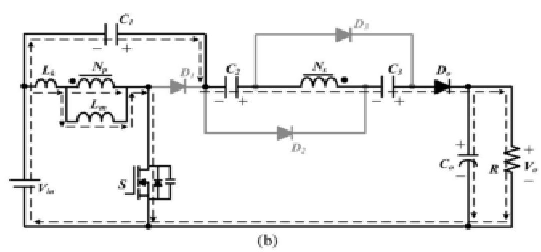


Fig.7. Mode II

Mode II [t1,t2]: During this time interval, S remains turned on. Diodes D_1,D_2, and D_3 are turned off, and D_o is turned on. L_m stores energy generated by dc source V_{in}. Some of the energy of dc source V_{in} transfers to the secondary side via the coupled inductor. Thus, the induced voltage V_{L2} on the secondary side of the coupled inductor makes V_{in} , V_{C1}, V_{C2}, and V_{C3}, which are connected in series, discharge to high-voltage output capacitor C_o and load R. This operating mode ends when switch S is turned off at t=t2.

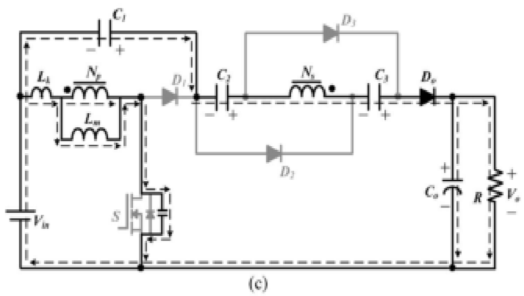


Fig.8. Mode III

Mode III [t2,t3]: During this time interval, S is turned off. Diodes D_1, D_2, and D_3 are turned off, and D_o is turned on. The energies of L_k and L_m charge the parasitic capacitor C_{ds} of main switch S. C_o provides its energy to load R. When the capacitor voltage V_{C1} is equal to V_{in} +V_{ds} at t=t3, diode D_1 conducts, and this operating mode ends.

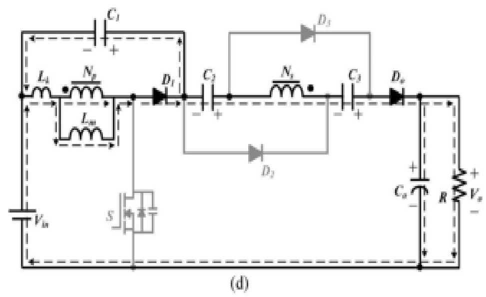


Fig.9. Mode IV

Mode IV[t3,t4]: During this time interval, S is turned off. Diodes D1 and Do are turned on, and D2 and D3 are turned off. The energies of L_K and L_m charge clamp capacitor C_1. The energy of L_k is recycled. Current i_{Lk} decreases quickly. Secondary-side voltage V_{L2} of the coupled inductor continues charging high-voltage output capacitor C_o and load R in series until the secondary current of the coupled inductor i_s is equal to zero. Meanwhile, diodes D_2 and D_3 start to turn on. WheniDois equal to zero at t=t4, this operating mode ends.

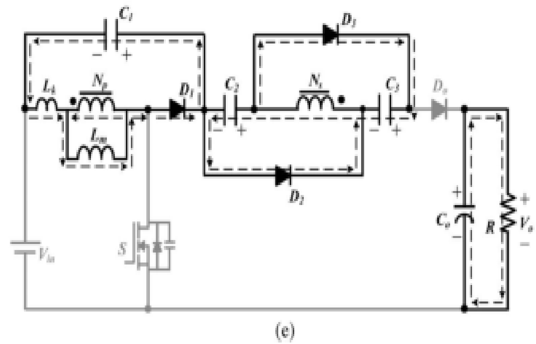


Fig.10. Mode V

Mode V [t4,t5]: During this time interval, Sis turned off. Diodes D_1, D_2, and D_3 are turned on, and D_o is turned off. C_o is discharged to load R. The energies L_k and L_m charge clamp capacitor C_1. L_m is released via the secondary side of the coupled inductor and charges capacitors C_2 and C_3. Thus, capacitors C_2 and C_3 are charged in parallel. As the energy of leakage inductor L_k charges capacitor C_1, the current i_{Lk} decreases, and i_s increases gradually. This mode ends at t=t6whenSis turned on at the beginning of the next switching period

6. Design and Analysis of High Step Up DC-DC Converter

The design consideration of high boost dc-dc converter is dicussed in this section.

Table I Design Parameters of High Step Up Dc-Dc Converters

Parameters	**Value**	**Unit**
Input voltage (Vin)	24	V
Output voltage (V_{out})	400	V
Output power (P_0)	200	W
Switching frequency (F_s)	50	kHz
Efficiency (Ƞ)	95.88	%
Turns ratio (n)	4	
Duty ratio (D)	0.648	
Ripple voltage(V_{ripple})	1.1	V

The leakage energy stored_in is recovered by the clamp capacitor such that the voltage of the switch is clamped. The clamp capacitor is discharged by the output rectifier current, which is equal to the reflected secondary current from the primary transformer winding. The primary transformer current equals the difference between the magnetizing current and the leakage inductor current.

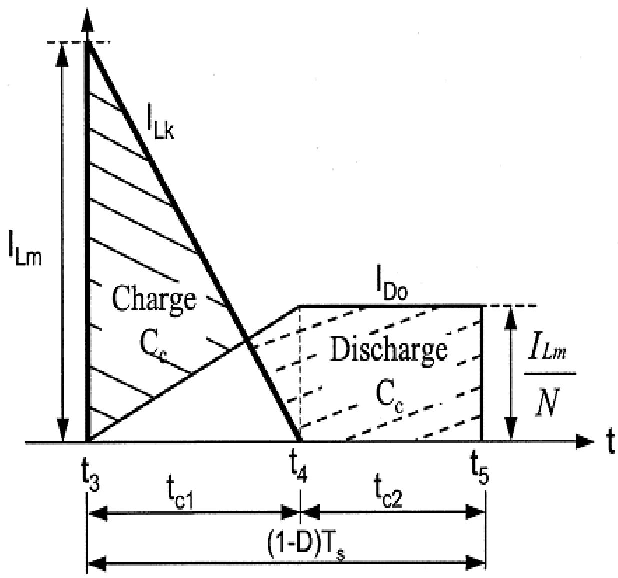


Fig.11. Relationship of clamp capacitor charge and discharge current.

Fig. 11 shows the relationship between the clamp capacitor charge and_discharge currents by assuming that the magnetizing current is ripple-free. The clamp capacitor needs to maintain a balance between charge and discharge. By making the charge area equal to the discharge area, the following relationship is found.

$$\frac{tc1}{T_S} = \frac{2}{n+1}(1-D) = D_{C_1} \qquad (1)$$

Where D is the duty ratio, tc1 is the time interval, Ts is the switching period, n is the turns ratio $=\frac{N_S}{N_P}$ and Dc1 is the energy release duty cycle.

Mode I and Mode III are significantly short, so we consider only Mode II, Mode IV and Mode V for CCM analysis.

In Mode II, the following equations are discussed.

$$V_{LK} = (1-k)V_{in} \qquad (2)$$

Where k is called coupling coefficient, $k = \frac{L_M}{L_M + L_K}$

$$V_{L1} = kV_{in} \qquad (3)$$

$$V_{L2} = nkV_{in} \qquad (4)$$

$$V_0 = V_{in} + V_{C1} + V_{C2} + V_{C3} + V_{L2} \qquad (5)$$

The voltage-second balance equation is

$$v(t) = L_M \frac{d_{im}}{d_t} \qquad (6)$$

Integrate this equation then

$$\int v(t)dt = \int L_m \dim \qquad (7)$$

$$I_m(t) - i_m(0) = \frac{1}{L_m}\int_0^t v(\tau)\,d\tau \qquad (8)$$

then $I_m(t) - i_m(0) = 0$ ie

$$\frac{1}{T_S}\int_0^{T_S} v(t)dt = 0 \qquad (9)$$

is called voltage-second balance equation. Applying this (9)

$$\int_0^{DT_s} v_{LK}{}^{II}\,dt + \int_{DT_s}^{T_s} v_{LK}{}^{V}\,dt = 0 \qquad (10)$$

$$\int_0^{DT_s} v_{L1}{}^{II}\,dt + \int_{DT_s}^{T_s} v_{L1}{}^{V}\,dt = 0 \qquad (11)$$

$$\int_0^{DT_s} v_{L2}{}^{II}\,dt + \int_{DT_s}^{T_s} v_{L2}{}^{V}\,dt = 0 \qquad (12)$$

Substitute (1)-(4) in (10)-(12). According to the sign conversion the voltages in Mode V can be derived as

$$v_{LK}{}^{V} = -\frac{D(n+1)(1-k)}{2(1-D)} v_{in} \qquad (13)$$

$$v_{L1}{}^{V} = -\frac{DK}{1-D} v_{in} \qquad (14)$$

$$v_{L2}{}^{V} = -\frac{nDK}{1-D} v_{in} \qquad (15)$$

In Mode V C_1, C_2, C_3 are charged. The voltages across the capacitors are,

$$v_{c1} = -v_{LK}{}^{V} - v_{L1}{}^{V} = \frac{D}{1-D} v_{in} \frac{(1+k)+(1-k)n}{2} \qquad (16)$$

$$v_{c2} = v_{c3} = -v_{L2}{}^{V} = \frac{nDk}{(1-D)} v_{in} \qquad (17)$$

Substitute (4),(16),(17) in (5) we get the voltage gain as

$$MCCM = \frac{v_0}{v_{in}} = \frac{1+nk}{1-D} + \frac{D}{1-D}\frac{(k-1)+n(1+k)}{2} \qquad (18)$$

At k=1 then voltage gain is written as

$$MCCM = \frac{1+n+nD}{1-D} \tag{19}$$

7. Closed Loop Simulation and Results

The parameters for simulation are given below

Table 1 Simulation Parameters

Parameters	**Value**	**Unit**
Input voltage (Vin)	24	V
Output voltage (V_{out})	400	V
Output power (P_0)	200	W
Switching frequency (F_s)	50	kHz
Efficiency (Ƞ)	95.88	%
Turns ratio (n)	4	
Duty ratio (D)	0.648	
Ripple voltage(V_{ripple})	1.1	V

Closed loop control of the high step up DC-DC converter is also simulated. Here PI controller with trial and error method is used for the closed loop operation. Here V_0 and V_{ref} is compared (400V) and the Error is given to PI Controller, where the values of PI controller are K_i=0.1 and the Settling time T_s= 0.12 sec.

Methods used for the output voltage regulations are Line regulation and Reference regulation.In line regulation, by varying the input voltage in a particular range the output will be constant, ie there is no variation in output value. The input voltage value will vary from 22V to 45V and the output will be 400V DC. For 22V settling time T_s=0.2sec, from 0.2 to 0.8sec the output voltage will be 400V.At 0.8sec input will change to 45V, there is some variation in output voltage and at 1.2 sec the output again constant.In reference regulation changing particular range of value the output will be that reference value. Here the value will vary from 300V to 450V.For 300V, T_s=0.3sec and for 450V settling time ,T_s=0.7sec.

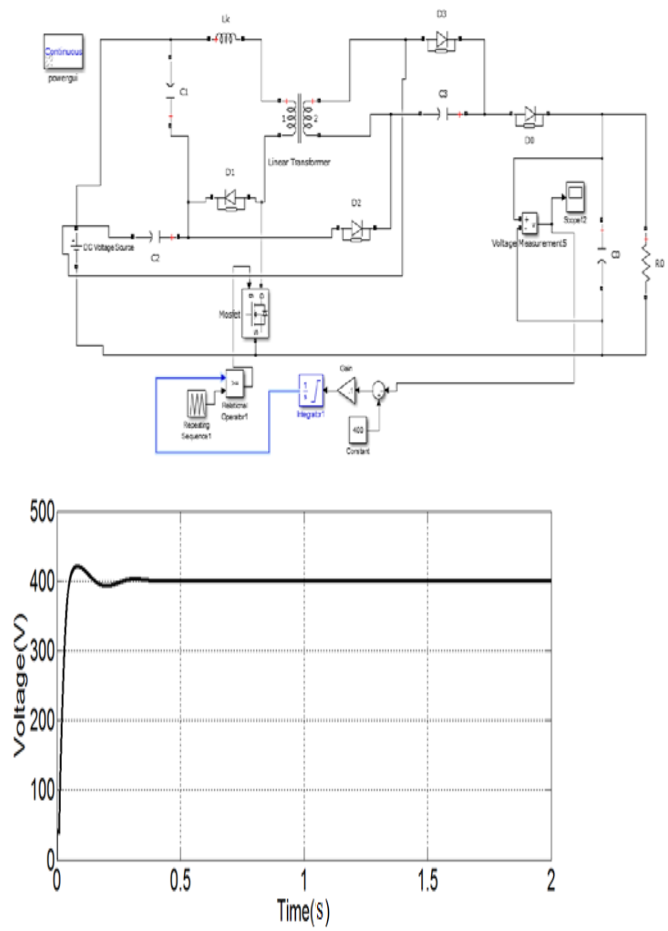
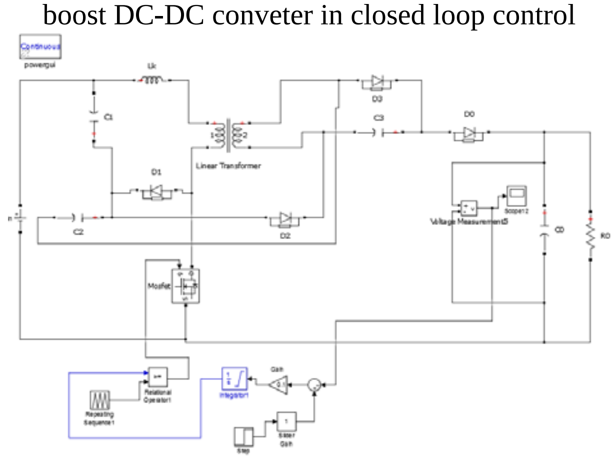


Fig.11. Simulation block and Waveform of high boost DC-DC conveter in closed loop control



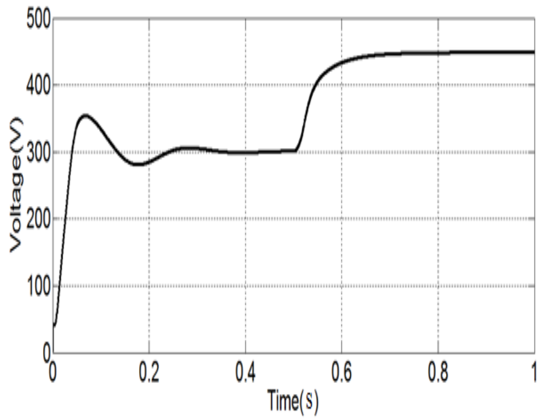


Fig.12. Simulation block and Waveform of high boost DC-DC converter with Reference regulation

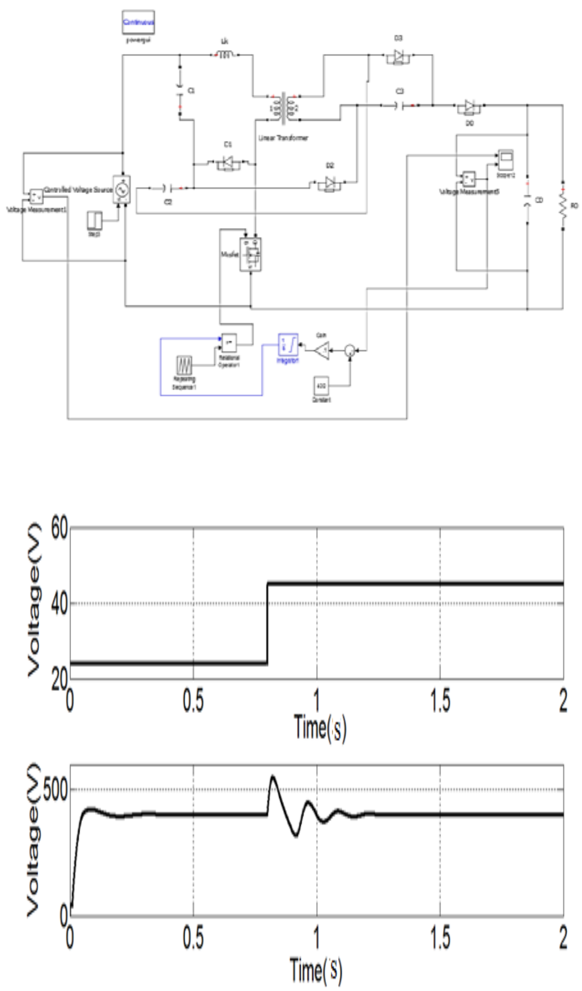


Fig.13. Simulation block and Waveform of high boost DC-DC conveter in closed loop control with Line regulation

8. Conclusions

A new boost converter with high voltage gain is proposed on this work. This converter is suitable for the applications with a high voltage gain between the input and the output. The proposed converter combines the concept of switched-capacitor and coupled-inductor techniques. The switched-capacitor technique proposed that capacitors can be parallel charged and series discharged to achieve a high step-up gain. This converter allows the utilization of MOSFET switch with lower conduction resistances RDS(On). Closed loop operation of dc-dc converter; line and reference regulations, principle of operation, theoretical analysis, and waveforms are discussed.

Acknowledgments

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Fig.12 Simulink model of high step up DC-DC co

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