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Voltage Regulated Single Switch DC-DC Converter with High Voltage gain

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***Abstract*—This paper develops a voltage regulated single switch DC DC converter with high voltage gain. The proposed converter is a non isolated structure using coupled inductor technique. For applications like uninterrupted power supply, electric traction etc a high voltage gain is required. In this paper, a high voltage gain is obtained by the coupled inductor and the diode-capacitor combination at the secondary side of the coupled inductor. The output voltage is regulated to obtain a constant value for small variations in the input. The clamp circuit connected to the primary winding of the coupled inductor clamps the voltage across the switch to a lower value. This enables the use of low voltage rating power devices. Efficiency increases as the leakage inductance energy is recycled.**

Keywords—coupled inductor, high voltage gain, voltage regulated

I. INTRODUCTION

We cannot imagine a world devoid of power. The need for power is thriving each day. The excessive use of fossil fuels has resulted in their depletion and various environmental problems. The energy from renewable resources needs to be depended more in the future.

For applications like uninterruptable power supply, photovoltaic generation system, electric traction etc a conventional boost converter is used for stepping up the input voltage. The drawback of this converter is high voltage stress across the switches and diodes. The voltage stress is equal to the output voltage. This increases the switching losses. So higher voltage rating switches have to be used. The efficiency of the conventional boost converter decreases with increase in duty ratio. So various voltage boosting topologies were introduced.

Switched capacitor based converters [2] - [3] consist of switches and capacitors only. Similarly switched inductor type converters [4] - [5] consist of switches and inductors. The drawback with these converters is the requirement of large number of switches and capacitors/ inductors for obtaining high voltage gain. This makes the circuit more complex and costly.

Non isolated converters like flyback converter, coupled inductor based converters were also used. The turns ratio of the transformer is adjusted in flyback converter to obtain high voltage gain. But the leakage inductance of transformer cause voltage spikes and increases the losses. Coupled inductor converters provide high voltage gain by compromising on the duty ratio.

In this paper, a single switch DC DC converter with high voltage gain is presented. The voltage gain of the converter is increased by the coupled inductor. The voltage gain is further increased by the diode- capacitor combination connected to the secondary winding of the coupled inductor. The output voltage is regulated to provide a constant voltage at the output for small variation in the input voltage. The voltage across the switch is clamped to a low voltage value by the clamp circuit connected to the primary winding of the coupled inductor. Hence, low voltage rating switches can be used. The leakage inductance energy of the coupled inductor is recycled and hence an increase in the efficiency can be observed.

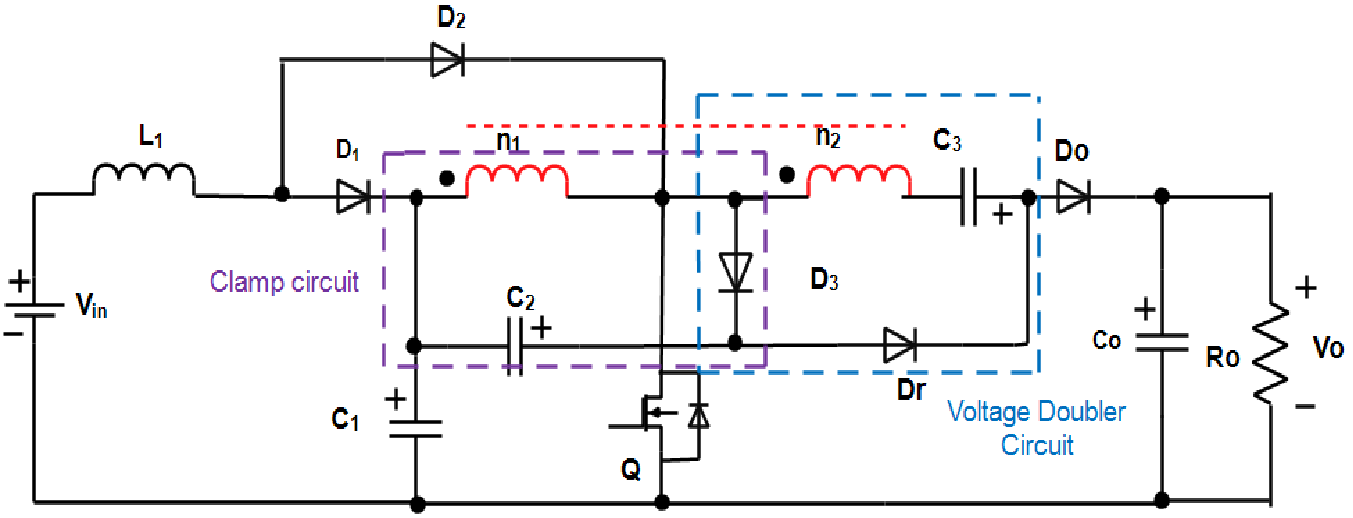
The outline of the paper is as follows:

Section II deals with the overall system configuration. This includes the circuit structure, equivalent circuit and assumptions for the analysis of the circuit. Modes of operation of the circuit is discussed in section III. The converter operates in five modes. Section IV is the steady state analysis. The voltage gain of the circuit, the voltage stress across the switches and diodes are derived in this section. Section V provides the simulation results. The simulation diagram, simulation parameters and simulation waveforms are provided. Conclusions from the results are provided in the section VI.

II. OVERALL SYSTEM CONFIGURATION

This section covers the circuit structure, the simplified equivalent circuit and assumptions taken into consideration for circuit analysis. The circuit structure is as in Fig.1. It consists of a single switch Q, coupled inductor T1, input inductor L_1, A clamp circuit with capacitor C_3 and diode D_3, voltage doubler cell with diodes D_3 and D_r and capacitor C_3. D_r is regeneration diode. The circuit has an output capacitor C_0, diodes D_1, D_2,

D_0. The couple inductor is modeled as an ideal transformer with N (n2/n1)as turns ratio. A parallel magnetizing inductance L_m and leakage inductance L_{K1} and L_{K2} are shown in the equivalent circuit Fig.2.



The assumptions considered for circuit analysis are as follows:

- All components are ideal except the leakage inductance of the coupled inductor T1.
- The input inductance L_1 is assumed to be sufficiently large so that the current through L_1 is continuous.
- The capacitors are assumed to be sufficiently large so that the voltage across the capacitors is constant
- The converter is working under continuous conduction mode. Both the inductors L_1 and L_m operate under continuous conduction mode.
- The duty ratio should be less than 0.7.

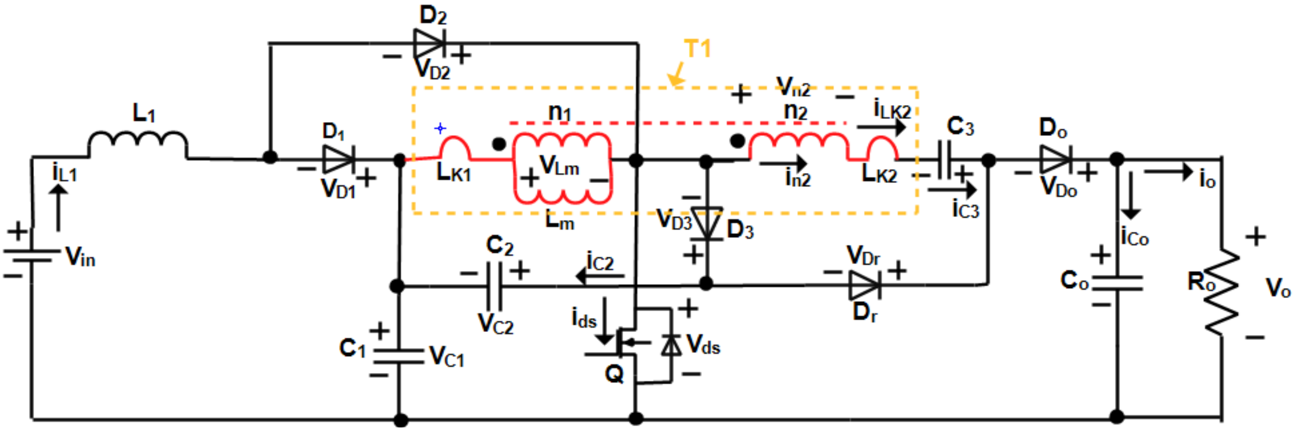


Fig. 2 Equivalent circuit of the proposed converter

In Fig. 2, input voltage is represented as Vin, the current through inductor L_1 as $I_{L1}$and voltage as V_{L1}. The voltage across the diodes D_1, D_2, D_3, D_r, D_o are represented as V_{D1}, V_{D2}, V_{D3}, V_{Dr}, V_{Do} respectively. The voltage across the capacitors C_1, C_2, C_3, C_o are represented as V_{C1}, V_{C2}, V_{C3}, V_{C0} respectively. The voltage across the output resistor R_0 is V_0 and the current through R_0 is i_0. The current through capacitor C_0 is i_{C0} and that across C_3 and C_2 is i_{C3} and i_{C2} respectively. The voltage across the magnetizing inductance L_m is V_{Lm}. The current through the leakage inductance L_{K1} and L_{K2} are i_{LK1} and i_{LK2} respectively.

III. MODES OF OPERATION

The circuit operates under continuous conduction mode. There are five modes of operation for the circuit. The waveforms of the converter are shown in fig.8

A. *Mode 1 (t_0 - t_1)*

Fig. 3 shows the equivalent circuit for Mode 1 operation of the converter. In this mode, at t = t_0, the switch Q is turned ON. The diodes D_2, D_r are forward biased and D_1, D_3, D_0 are reverse biased. The voltage across the diodes D_1, D_3 and D_0 are V_{C1}, $V_{C1} + V_{C2}$ and $V_0 - V_{C1} - V_{C2}$ respectively. The current flow path is shown in Fig. 3 with dotted arrows. The input voltage is transferred to the inductor L_1 through D_2 and Q. The inductor charges and hence the inductor current i_{L1} increases linearly. The capacitor C_1 discharges through the magnetizing inductance Lm, leakage inductance L_{K1} and he switch Q. So the primary voltage of the coupled inductor is

V_{C1}. The capacitors C_1 and C_2 discharges through diode D_r and charges C_3. Output power is supplied by the capacitor C_0.

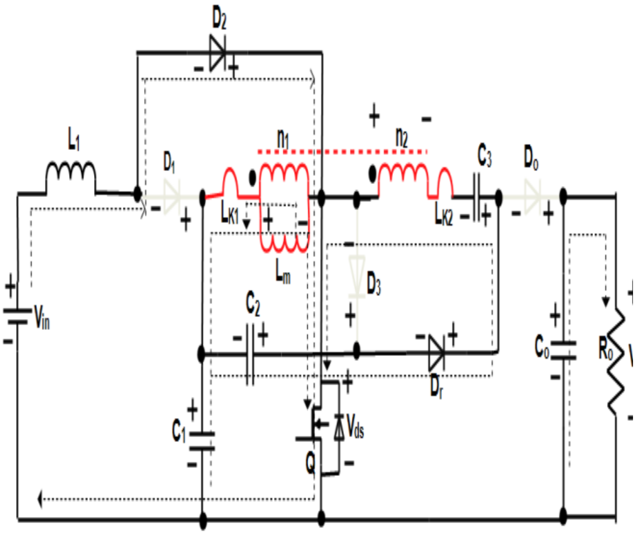


Fig. 3 Equivalent circuit for Mode 1 operation of the proposed converter

B. *Mode 2 ($t_1 – t_2$)*

Fig 4 shows the equivalent circuit for mode2 operation . At t = t_1, the switch Q is turned OFF. The diode D_1, D_3 and D_r are forward biased. Diodes D_2 and D_0 are reverse biased. The voltage across diode D_2 is V_{C2} and that across diode D_0 is $V_0 – V_{C1}$ - V_{C2}.The current through Q in stage 1 is forced to flow through D_3 in this stage. The inductor L_1 discharges through the diode D_1 and charges the capacitor C_1. The inductor current i_{L1} decreases linearly. The energy stored in L_{K1} discharges through the diode D_3 and charges the capacitor C_2. Here, the energy stored in inductor L_{K1} is recycled to capacitor C_2. The energy stored in inductor L_{K2} discharges through the diode D_3 and D_r and charges the capacitor C_3. The output power is supplied by the capacitor C_0. The voltage stress across the switch Q is V_{C1} + V_{C2}. At t = t_2, the inductor current i_{LK2} reaches zero.

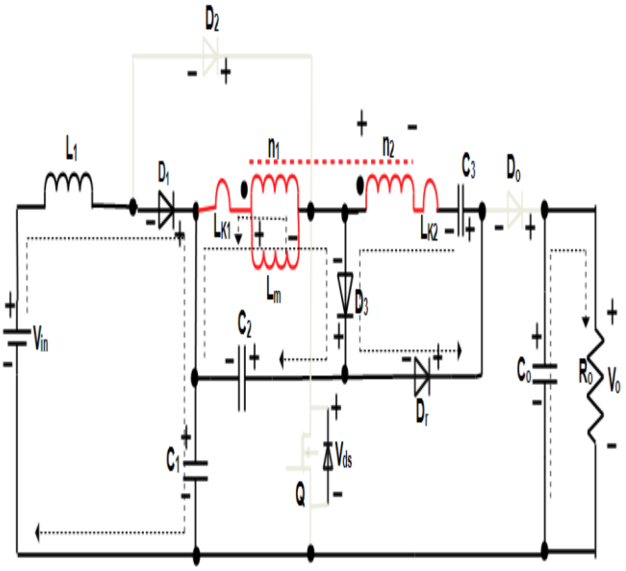


Fig.4 Equivalent circuit for Mode 2 operation of the proposed converter

C. *Mode 3 ($t_2 – t_3$)*

Fig.5 shows the equivalent circuit for mode 3 operation. At t = t_2, the inductor current i_{LK2} reaches zero and the switch Q remains in OFF state. Diodes D_2 and D_r are reverse biased and D_1, D_3 and D_0 are forward biased. The voltage across diode D_2 is $–V_{C2}$ and that across diode D_r is $V_{C3} + NV_{C2}$. The inductor L_1 continues discharging through the diode D_1 and charges the capacitor C_1. The inductor current i_{L1} keeps on decreasing linearly. The energy stored in L_{K1} discharges through the diode D_3 and charges the capacitor C_2. The energy stored in inductor L_m also discharges through n_2 and C_3 and provides the output voltage. Here, the leakage inductor energy is recycled. The voltage stress across the switch Q is V_{C1} + V_{C2}. At t = t_3, i_{LK1} = i_{LK2} and the current through the capacitor C_2 (i_{C2}) is zero.

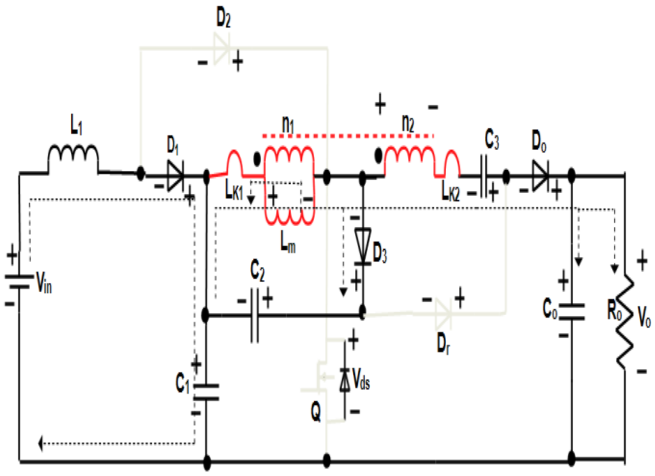


Fig. 5 Equivalent circuit for Mode 3 operation of the proposed converter

D. *Mode 4 ($t_3 – t_4$)*

Fig. 6 shows the equivalent circuit for mode 4 operation. The switch Q continue to remain in OFF condition. The diodes D_2, D_3, D_r are reverse biased. Diodes D_1 and D_0 are forward biased. The inductor current continue decreasing as the energy stored in inductor L_1 discharges through the diode D_1 to charge the capacitor C1. The input voltage Vin, inductor L_1, L_m, L_{K1}, winding n_2, L_{K2} and C_3 are connected in series and this providesthe output power at the load R_0. At t = t_4, switch Q is turned ON.

E. *Mode 5 ($t_4 – t_5$)*

Fig. 6 shows the equivalent circuit for 4 operation. At t = t_4, switch Q is turned ON. Diodes D_1, D3, Dr are reverse biased. The voltage across the reverse biased diodes are V_{C1}, $V_{C1} + V_{C2}$, $V_0 – V_{C1} – V_{C2}$ respectively. The diode D_2 and D_0 are forward biased. The inductor L_1 charges through the diode D_1. So the inductor current increases linearly. The capacitor C_1 discharges through L_m and L_{K1}. So the current through the inductors increases linearly. The magnetizing inductor L_m transfers its energy to the load through the secondary winding. At $t = t_5$, the current through L_{K2} decreases to zero and $i_{Lm} = i_{LK1}$.

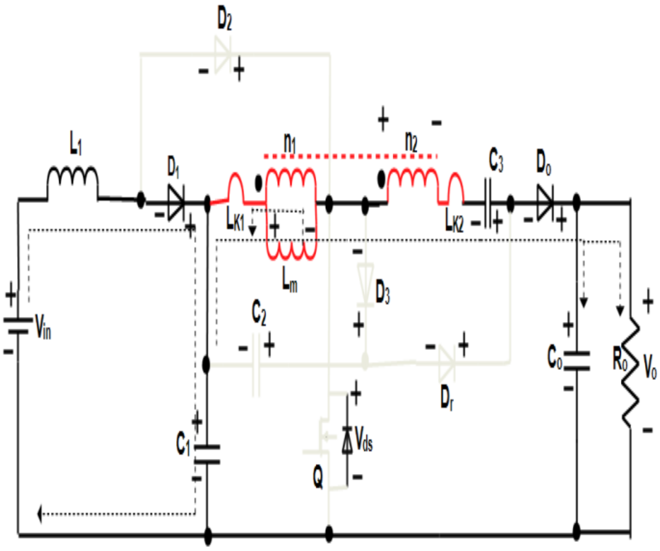


Fig.6 Equivalent circuit for Mode 4 operation of the proposed converter

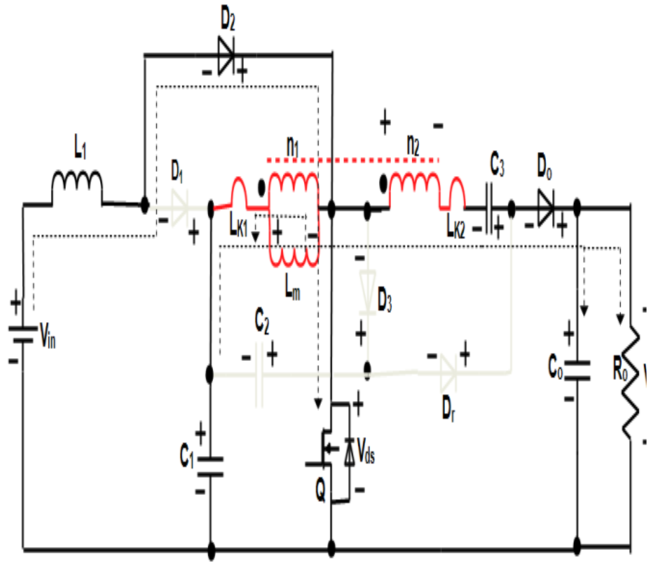


Fig. 7 Equivalent circuit for Mode 5 operation of the proposed converter

IV. STEADY STATE ANALYSIS

A lossless power condition is assumed for the steady state analysis. The leakage inductances of the coupled inductor are neglected. Mode 1 and Mode 3 are only considered for the analysis as the time duration of other modes are very small. From Mode 1, the following equations are obtained.

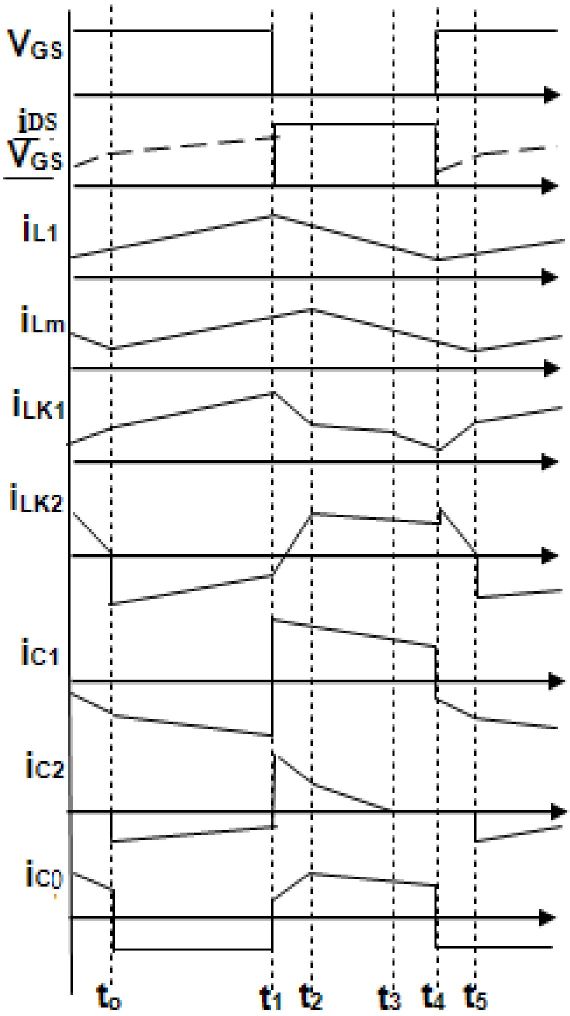


Fig. 8 Theoretical waveforms of the proposed converter

$$V_{L1} = V_{in} \quad (1)$$

$$V_{Lm} = V_{C1} \quad (2)$$

$$V_{C3} = NV_{C1} + V_{C1} + V_{C2} \quad (3)$$

From Mode 3, the following equations are obtained.

$$V_{L1} = V_{in} - V_{C1} \quad (4)$$

$$V_{Lm} = - V_{c2} \quad (5)$$

$$V_0 = V_{C1} + (N + 1)V_{C2} + V_{C3} \quad (6)$$

Using the volt second balance principle to inductor L_1 and L_m, the following equations are obtained.

$$V_{in}DT_s + (V_{in} - V_{C1})(1-DT_s) = 0 \quad (7)$$

$$V_{C1}DT_s + (- V_{C2})(1-DT_s) = 0 \quad (8)$$

The voltage across the capacitors C1, C2 and C3 can be derived from “(1)” – “(8)”

$$V_{C1}=\frac{V_{in}}{(1-D)}=\frac{(1-D)V_0}{(2+N)} \quad (9)$$

$$V_{C2}=\frac{DV_{in}}{(1-D)^2}=\frac{DV_0}{(2+N)} \quad (10)$$

$$V_{C3}=\frac{(N+1-DN)V_{in}}{(1-D)^2}=\frac{(N+1-DN)V_0}{(2+N)} \quad (11)$$

Substituting “(9)”, ”(10)”, “(11)” in “(6)”, voltage gain is obtaines as :

$$M=\frac{V_0}{V_{in}}=\frac{(2+N)}{(1-D)^2} \quad (12)$$

The maximum voltage stress across the switch Q is derives as:

$$V_{max}Q=\frac{V_0}{(2+N)} \quad (13)$$

Comparing the conventional boost converter with the proposed converter, the voltage stress across the switch is reduced . The voltage stress across the switch in conventional boost converter is V_0. In the proposed converter the voltage stress across the switch decreases as turns ratio increases.

The voltage stress across the diodes are obtained as:

$$V_{stress}D_1=V_{C1}=\frac{V_{in}}{(1-D)}=\frac{(1-D)V_0}{(2+N)} \quad (14)$$

$$V_{stress}D_2=V_{C2}=\frac{DV_{in}}{(1-D)^2}=\frac{DV_0}{(2+N)} \quad (15)$$

$$V_{stress}\ D_3 = V_{C1} + V_{C2} = \frac{V_{in}}{(1-D)^2} = \frac{V_0}{(2+N)} \quad (16)$$

$$V_{stress}D_0 = V_0 - V_{C1} - V_{C2} = \frac{(1+N)V_{in}}{(1-D)^2} = \frac{(1+N)V_0}{(2+N)} \quad (17)$$

$$V_{stress}\,D_r = V_0 - V_{C1} - V_{C2} = \frac{(1+N)V_{in}}{(1-D)^2} = \frac{(1+N)V_0}{(2+N)} \quad (18)$$

The voltage stress across the diode in the conventional boost converter is V_0. The above equations show that the voltage stress across diodes is reduced in the proposed converter.

The turns ratio of the coupled inductor T1 can be calculated by substituting “(9)”, “(10)” and “(11)” in “(6)” as:

$$N=\frac{V_0}{V_{in}}(1-D)^2-2 \quad (19)$$

V. SIMULATION RESULTS

The proposed converter was simulated using Matlab Simulink 2009b. The converter was designed and simulated for an output power of 50Watt. The input voltage is 10V and the converter generates an output of 120Volt. In order to regulate the output voltage a PI controller is used. The output from the converter is measured and compared with a constant voltage of 120Volt. The error is given to a PI controller to reduce the steady state error. The output from the saturation block is compared with a saw tooth waveform to generate the switching pulses.

A. *Simulation Parameters*

The values for various components are as given in Table.1. The output voltage remains at 120 Volt for small variations in the input voltage. Hence voltage regulation is attained. Fig. 9 shows the simulation diagram.

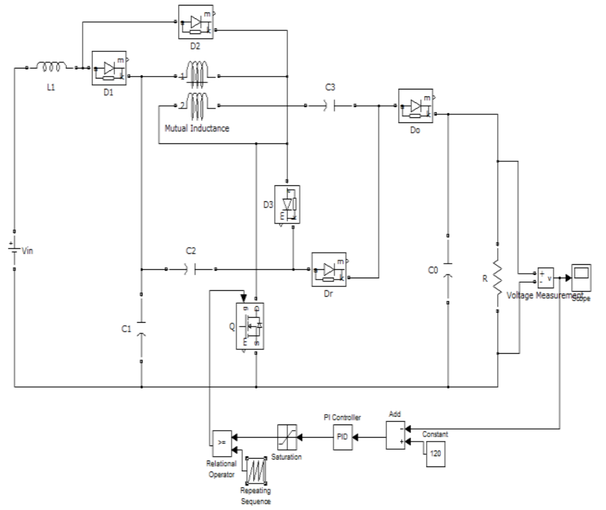


Fig.9 Simulation Diagram

The output voltage waveform is as in Fig. 10. For an input voltage of 10 volt an output of 120 volt is obtained. Fig. 11 shows the switching pulse applied to the switch Q. The voltage and current through the switch is as shown in Fig.12. Fig.13 shows the inductor current $i_{L1.}$ The current through primary and secondary leakage inductor is shown in Fig 14 and Fig. 15 respectively. The capacitor currents iC1, iC2, iC0 are shown in Fig. 16, Fig. 17, Fig.18 respectively. The voltage stress across the diodes is shown in Fig.19.

TABLE 1. Simulation parameters

Simulation parameters	Values
Output power	50 W
V_{in}	10V
V_0	120V
fs	40kHz
$N = n_2/n_1$	2
Lm	370µH
L_1	60µH
C_1	470µF
C_2	47µF
C_3	47µF
C_0	470µF

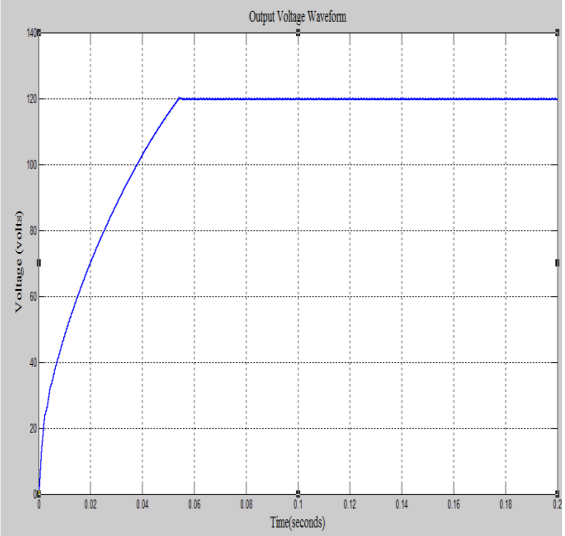


Fig. 10 Output Voltage Waveform

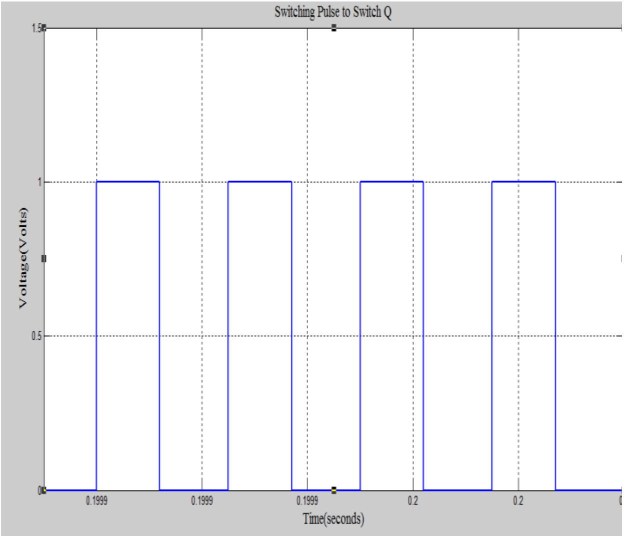


Fig. 11 Switching pulses to the switch Q

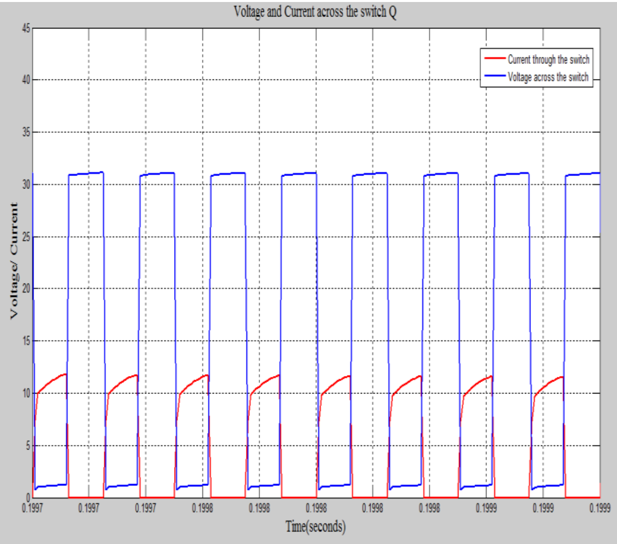


Fig. 12 Voltage and current waveforms across switch Q

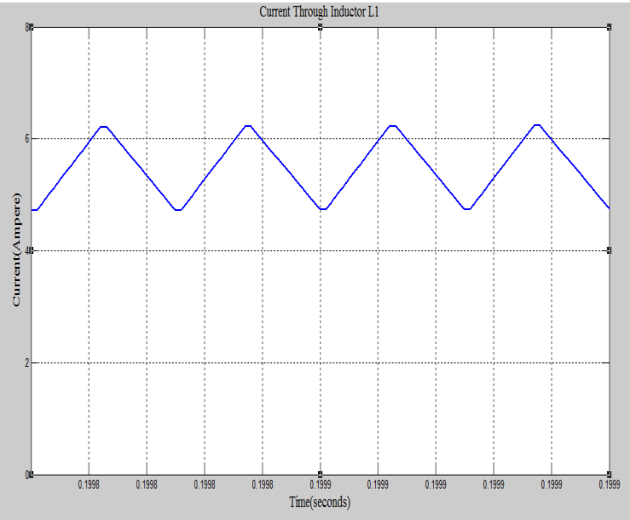


Fig. 13 Current through the inductor L_1

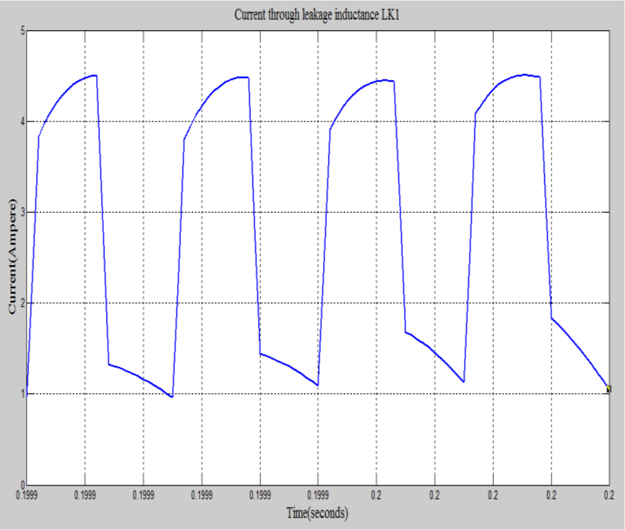


Fig. 14 Current through primary leakage inductor L_{K1}

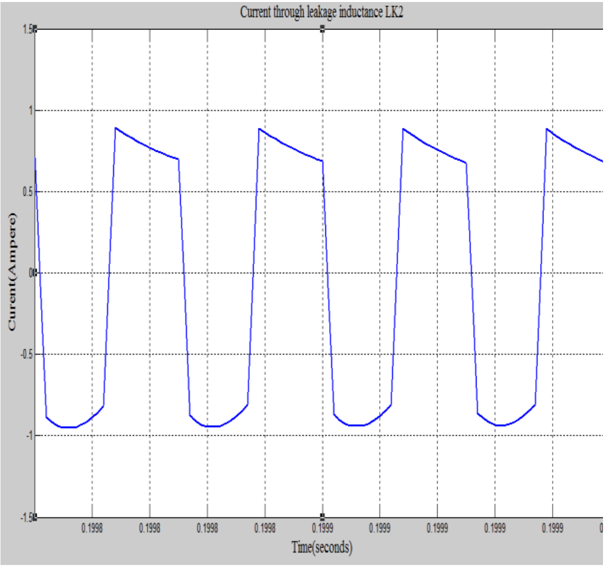


Fig. 15 Current through secondary leakage inductor L_{K2}

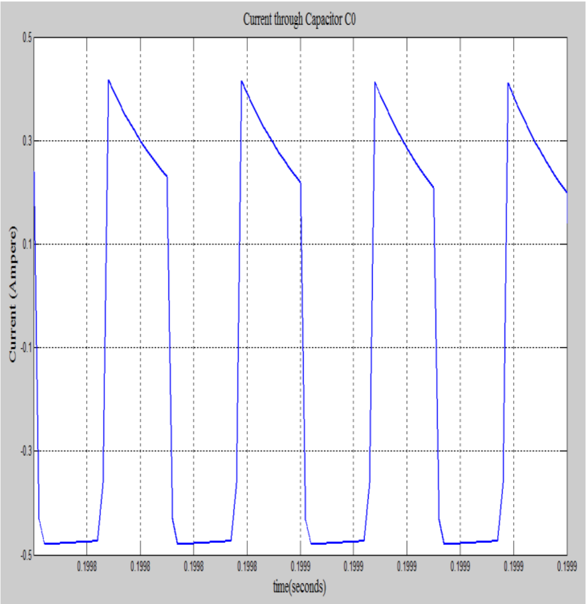


Fig.18 Current through the capacitor C_0

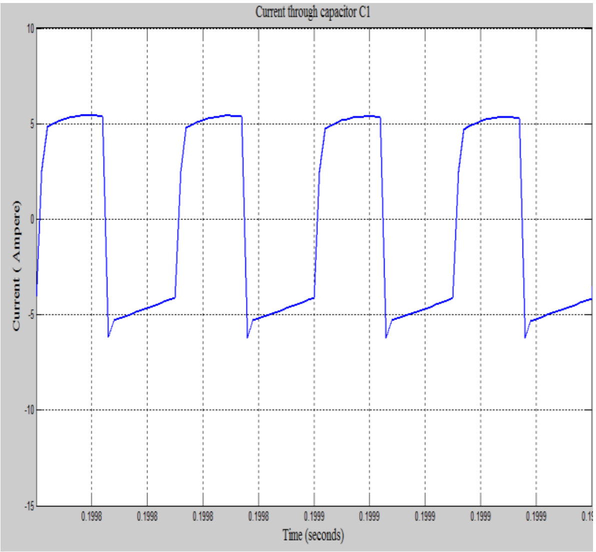


Fig. 16 Current through the capacitor C_1

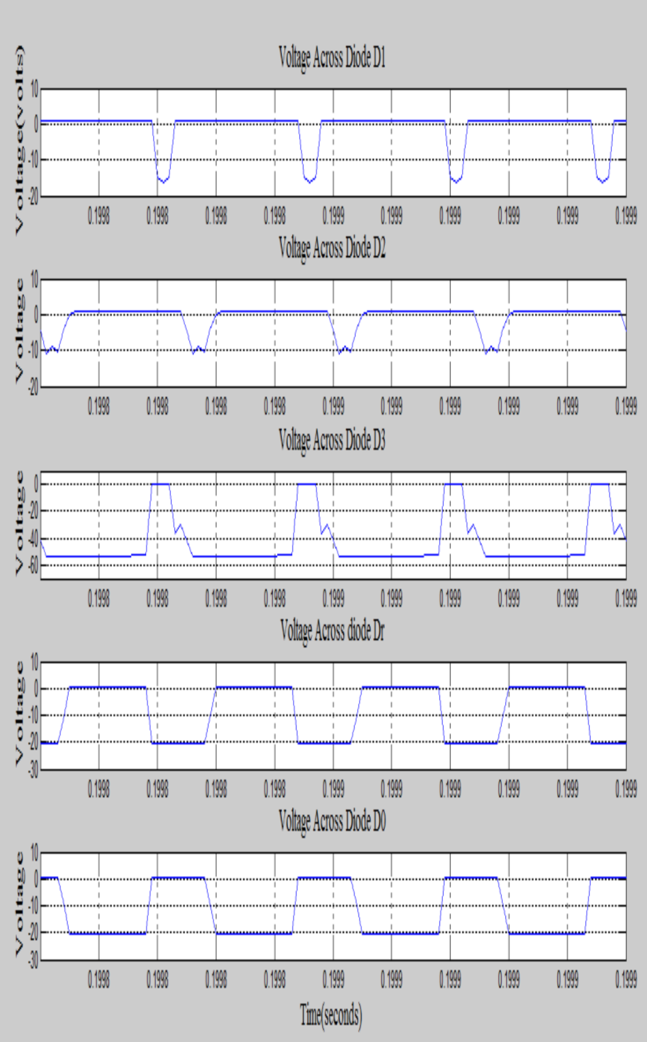


Fig.19 Voltage stress across the diode D_1, D_2, D_3, D_r, D_0

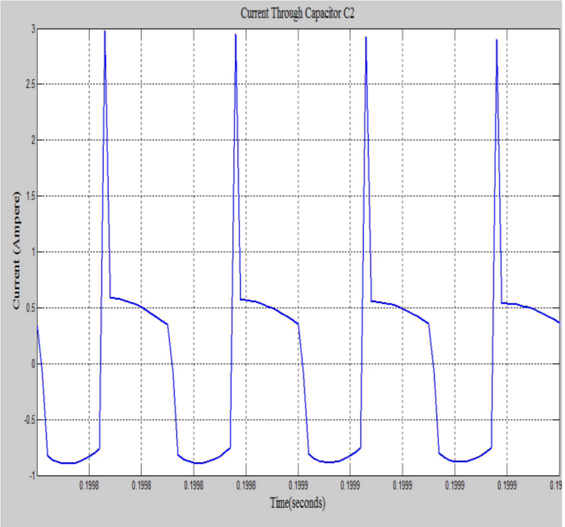


Fig. 17 Current through the capacitor C_2

VI. CONCLUSION

A single switch DC DC converter with high voltage gain is presented in this paper. The voltage gain of the converter is increased by the coupled inductor. The voltage gain is further increased by the diode- capacitor combination connected to the secondary winding of the coupled inductor. The output voltage is regulated to provide a constant voltage at the output for small variation in the input voltage. The voltage across the switch is clamped to a low voltage value by the clamp circuit connected to the primary winding of the coupled inductor. Hence, low voltage rating switches can be used. The leakage inductance energy of the coupled inductor is recycled and hence an increase in the efficiency can be observed. The converter was simulated using Matlab Simulink 2009b and the output waveforms obtained were as per the theoretical values. With 50 Watt power, an input of 10 Volt produces an output of 120 Volt with a switching frequency of 40 kilo Hertz. The voltage stress across the switch is 30 Volt. This shows that the voltage stress across the switch is reduced comparing with conventional boost converter. The voltage stress across the diodes are also reduced in the proposed converter.

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