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Paper Authors

KONDA VENKATA LAKSHMI RAJA DEEPTHI, RAJU LAKSHMANA REDDY

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A NOVEL METHOD OF AUTOTRANSFORMER AND COUPLED INDUCTOR BASED CLOSED LOOP CONTROL OF HIGH-STEP-UP DC-DC CONVERTER

[1]KONDA VENKATA LAKSHMI RAJA DEEPTHI, [2]RAJU LAKSHMANA REDDY M-Tech

[1]M-tech student Scholar Department of Electrical & Electronics Engineering, Velaga Nageswara Rao College of Engineering, Ponnuru; Guntur (Dt); A.P, India.
[2]Associate Professor Department of Electrical & Electronics Engineering, Velaga Nageswara Rao College Of Engineering, Ponnuru; Guntur (Dt); A.P,

Abstract: In this paper, a coupled inductor and autotransformer based high step-up dc–dc converter is proposed. The converter utilizes an integrated autotransformer and a coupled inductor on the same core to achieve a high step-up voltage gain without extreme duty cycle. In addition, the energy stored in the coupled inductor is recycled; the voltage stress of the main switch is reduced. The switch with low resistance $R_{DS\ (ON)}$ can be adopted to reduce the conduction loss and the reverse-recovery problem of the diodes is alleviated. Not only lower conduction losses but also higher power conversion efficiency is benefited from lower turns ratios. The derivative circuit design and its implementation with closed loop control are given with operational results.

Key Words: dc-dc power conversion, coupled inductor, autotransformer, and distributed generation.

I. INTRODUCTION

In recent years, air pollution and energy shortage have become major national concerns. When the global temperature increases by 1◦C, the sea level will increase by 2.3 m [1]. This phenomenon will considerably affect human life and safety. Therefore, previous studies have attempted to finda solution, hoping to solve the problems of air pollution, global warming, and energy shortage by using highly efficient renewable energy systems. The current more mature and widely used renewable energy sources include solar, wind, and tidal energy sources [2–4]. Often these renewable energy sources have low-voltage output and must pass through a set of high boost converter circuits to increase the voltage, and then through a DC-AC inverter to convert AC voltage from the main supply in parallel. Therefore, a DC-DC high boost ratio circuit affects the overall efficiency of the system [5–8].The conventional DC-DC boost circuit is not applied in high boost ratio applications. In an ideal scenario, when the duty cycle in a conventional boost circuit increases to 1 (unity), the boost conversion ratio reaches infinity. However, high step-up gain is limited by the capacitor, inductor main power switch, and resistance, because electromagnetic interference and reverse-recovery issues are encountered at extreme duty cycles. Moreover, the leakage inductance of the transformer will cause high power dissipation and high voltage spikes on the main power switch. Therefore, a main powerswitch with high stress voltage must be selected because of excessive cost and space issues.

In particular, switch capacitor [9–13], coupled inductor [14–21], and voltage lift [22,23]techniques have been proposed. A coupled inductor step-up circuit with a simple inductive windingstructure was used to achieve low voltage stress of the main switch and a high voltage conversion ratio.Therefore, this architecture is commonly used. However, the main drawback of this architecture isthat the coupled inductor has a considerable leakage inductance; this leakage inductance and parasiticcapacitance on the switch will resonate and cause voltage spikes. To solve the problems causedby leakage inductance, capacitors, resistors, and diodes comprising a snubber circuit can be used;however, the energy is consumed in the resistance, thus reducing circuit efficiency. Switched capacitorand voltage lift technology can achieve a high boost ratio function but the main switch suffers ahigh transient current, and the conduction loss is increased. A switched-clamp capacitor can storeenergy when the switch is turned on. When the power is switched off afterwards, the energy in thecapacitor is delivered to the output loading. However, the electric system prevents current flow andno direct conduction path is permitted. The voltage lift technique is similar the Cuk converter or thesingle-ended primary inductor converter (SEPIC) converter, the energy transfer from one inductorvia the intermediate capacitor and then to the other inductor. Therefore, the transferred energy ismainly determined by the capacitance, thus causing the current stress on the capacitor to be serious.The coupled-inductor technique can achieve high step-up gain by adjusting the turn ratio. However,the inductor leakage issue relates to the voltage spike on the power switch. Therefore, this study used acoupled inductor step-up circuit with a clamp circuit, which absorbed energy from the leakage inductorof the coupled inductor and supply the energy back to the output terminal of the capacitor duringthe next period [24,25]. Using a clamp circuit prevents spikes on the switch, and the main switchvoltage stress is clamped at a voltage of 1/7 Vo. Moreover, the booster-circuit integrates a boost-flybackconverter with switched capacitor architecture to achieve a high step-up ratio.This circuithas boostand flyback type features. When the switch is turned on, the first boost stage is similar to a boostconverter combined with a switched capacitor converter. Conversely, when the switch is turned off,the second boost stage is similar to the flyback and switched capacitor converters [26–34]. The newproposed converter architecture can achieve a high step-up ratio by adjusting the duty cycle; a clampcircuit is used for energy recovery by the leakage inductor of the coupled inductor to achieve highefficiency and step-up ratio.

The main objective is to improve the Voltage Gain of the Step-up Converter and also to reduce Voltage stress of the circuit. Further the Voltage Drift problem is reduced using closed loop control of the proposed converter with PI controller. The output voltage from the converter is fed as feed back to the PI; there it compares the feedback voltage signal and the reference voltage signal to produce PWM pulse which triggers the main switch of the converter.

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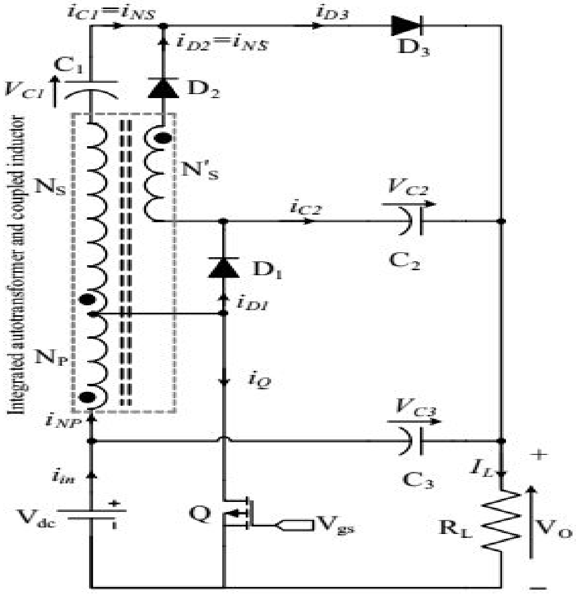
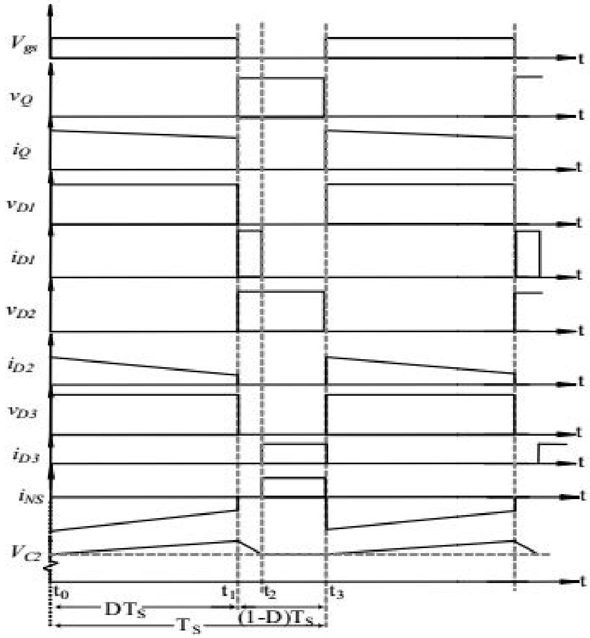
II. PROPOSED TOPOLOGY AND PRINCIPLE OF OPERATION

The proposed converter consists of an autotransformer and a coupled inductor wound on the same core and three diodes and the same number of capacitors as shown in Fig.1 (a). The advantage of the proposed topology are: (1) very high voltage gain, which is particularly suitable for (a) low voltage output Fuel Cell (25 – 50 V) to stabilize the output voltage to 400 VDC and, (b) high voltage Light Emitting Diode (LED) lamps (which require 100– 600 V for a series/parallel string of LED from a battery input of 12 – 24 V), (2) low voltage stresses on switch (Q), (3) no voltage spikes across the switch (diode D_1 and capacitor C_2 forms are generative snubber for the switch Q), and (3) only eight components are required to design the converter. The winding design is simplified by winding the autotransformer and coupled inductor on the same core that reduces the space and the component count.



(a)



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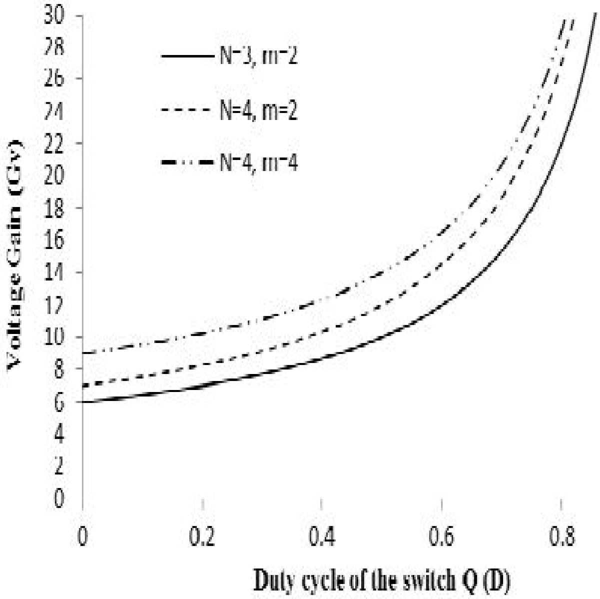
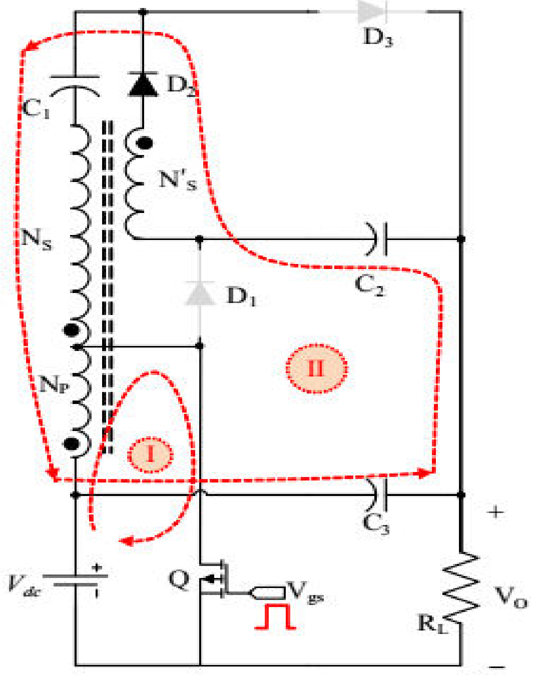
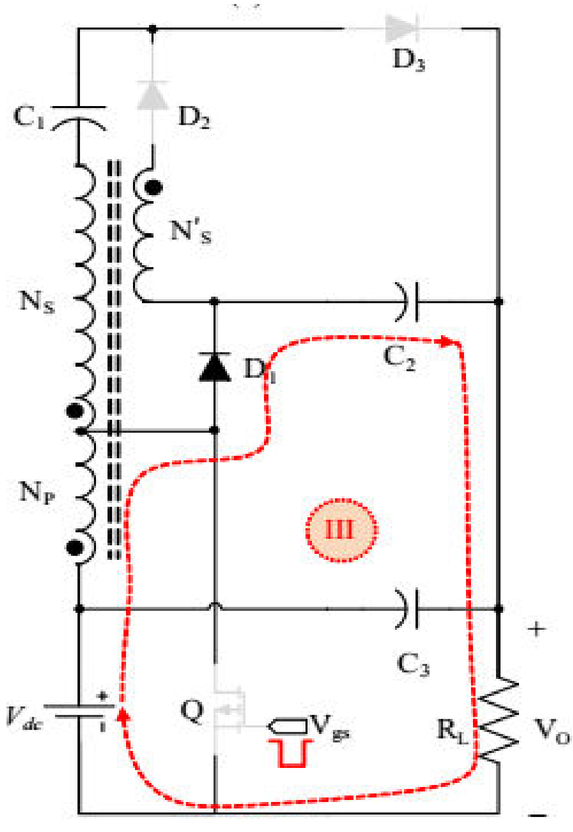


(c)

Fig.1 (a) Schematic of proposed ultra-step-up dc-dc converter and its (b) steady-state waveforms in Continuous Conduction Mode (CCM) operation and (c) theoretical voltage transfer characteristics



(a)



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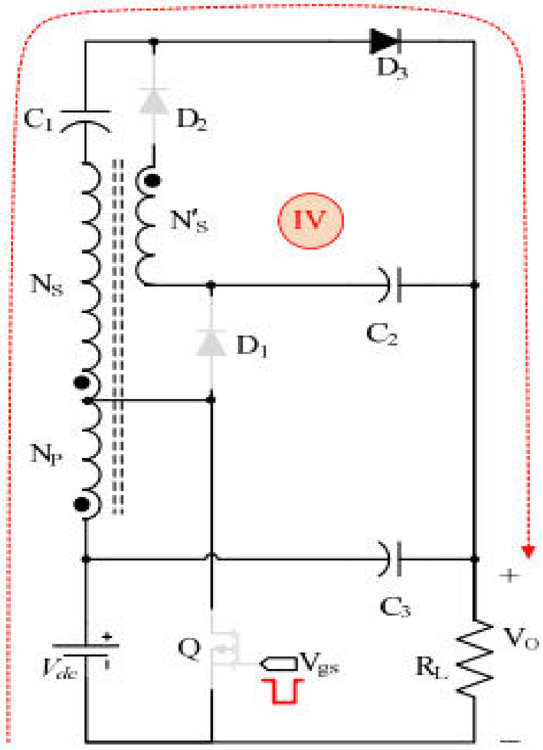

(c)

Fig.2. Equivalent circuit of the proposed converter during different operating modes: (a) Mode 1 [t_0-t_1], (b) Mode 2 [t_1-t_2], and (c) Mode 3 [t_2-t_3].

The steady-state waveforms of the proposed converter operating in Continuous Conduction Mode (CCM) are depicted in Fig.1 (b). The converter has three operating mode in a switching period. The equivalent circuit of the converter in each operating mode is shown in Fig.2 (a)-(c). Each mode is described briefly as follows:

Mode 1 ([t_0-t_1]): During this interval, the switch Q turns-on and current flows through the primary winding, secondary winding of the autotransformer and on the coupled inductor through diode D_2 and charge capacitor C_1 and C_2. Diode D_1 and D_3 are reversed biased. There are two closed loops for the current to flow as shown in Fig.2 (a). The relevant circuit expressions for this mode can then be written like in (1) and (2), where V_L is the voltage across the primary inductor winding (Np).

$$\frac{N_S}{N_P}v_L + V_O - V_{C2} + \frac{N_S'}{N_P}v_L - V_{C1} = 0$$

$$\Rightarrow\ v_L = (V_{C1} + V_{C2} - V_O)/((N_S + N_S')/N_P) \tag{1}$$

$$\textbf{And } \boldsymbol{V_L = V_{dc}} \tag{2}$$

From (1) and (2)

$$V_{C1} + V_{C2} = \frac{N_S+N_S'}{N_P}V_{dc} + V_O \tag{3}$$

Mode 2 ([t_1-t_2],]): The switch is turned-off during this interval. Diode D_2 is reverse biased, whilst diode D_3 continue its reverse biased until the end of this mode. The load current flows through diode D_1 and primary winding of an autotransformer, and discharge the capacitor C_2. The circuit expression for this mode can then be written as (4)

$$V_{dc} - v_L + V_{C2} - V_O = 0$$

$$\Rightarrow v_L = V_{dc} + V_{C2} - V_O \tag{4}$$

Mode 3 ([t_2-t_3]**):** The diode D_1 remains on in the previous mode until capacitor C_2 is discharged to Vc_2. This reverse biasing the diode D_1 and the load current path changes to loop IV as shown in Fig.2 (c). The circuit expression for this mode can then be written as (5)

$$V_{dc} - v_L - \frac{N_S}{N_P}v_L + V_{C1} - V_O = 0$$

$$\Rightarrow v_L = -\frac{V_{C1}-V_O-V_{dc}}{\frac{N_S+N_P}{N_P}} \tag{5}$$

Applying volt-sec balancing to (2) and (4) further results in (6), where D represents duty cycle of Q.

$$\int_0^{DT_s} v_L dt + \int_{DT_s}^{T_s} v_L dt = 0$$

$$\Rightarrow DV_{dc} + (1-D)(V_{dc} + V_{C2} - V_O)$$

$$\Rightarrow V_{C2} = (V_O(1-D) - V_{dc})/(1-D) \tag{6}$$

Applying volt-sec balancing to (1) and (5) further results in (7).

$$\int_0^{DT_s} v_L dt + \int_{DT_s}^{T_s} v_L dt = 0$$

$$\frac{(V_{C1}+V_{C2}-V_O)}{\frac{N_S+N_S'}{N_P}}D - \frac{(V_{C1}-V_O-V_{dc})}{\frac{N_S+N_P}{N_P}}(1-D) = 0 \tag{7}$$

The voltage gain (Gv) and hence the voltage transfer characteristics equation of the converter is found by solving (3) and (7) as

$$G_v = \frac{V_O}{V_{dc}} = \left[\frac{1+N}{1-D} + m\right] \tag{8}$$

Where, $N = (N_P+N_S)/N_P$ is the autotransformer voltage transfer constant and $m = N'_S/N_P$ is the turns ratio of the coupled inductor. The voltage transfer characteristic of the proposed converter is shown in Fig.1 (c) with varying N, m and D.

III. CONTROL STRATEGY

In order to achieve good voltage regulation closed loop control methods are introduced. In pulse width modulation (PWM) control, the duty ratio is linearly modulated in a direction that reduces the error. When the input voltage is perturbed, that must be sensed as an output voltage change and error produced in the output voltage is used to change the duty ratio to keep the output voltage to the reference value. The main switch is fabricated from an integrated power process, the layouts can be changed to vary the parasitic, however design of switch layout is complex, fixed frequency and constant duty ratio must be maintained. This converter provides high voltage gain and can be employed for high power applications however the duty ratio is limited to 0.85. In this, the energy of the leakage inductor is recycled to the output load directly, limiting the voltage spike on the main switch. To achieve a high step-up gain, it has been proposed that the secondary side of the coupled inductor can be used as fly back and forward converters. In some converters voltage gain is improved through output voltage stacking.

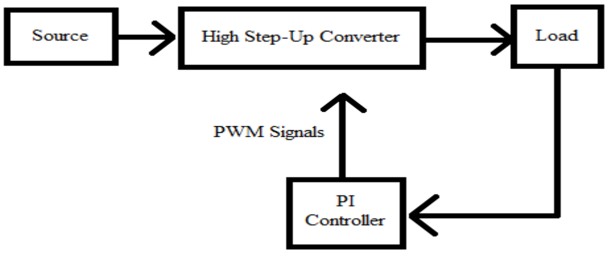

Fig.3 Block Diagram

IV. MATLAB/SIMULINK RESULTS

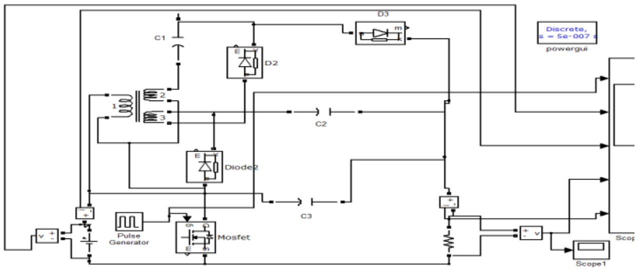

Fig.4 matlab/Simulink model of proposed converter in open-loop method

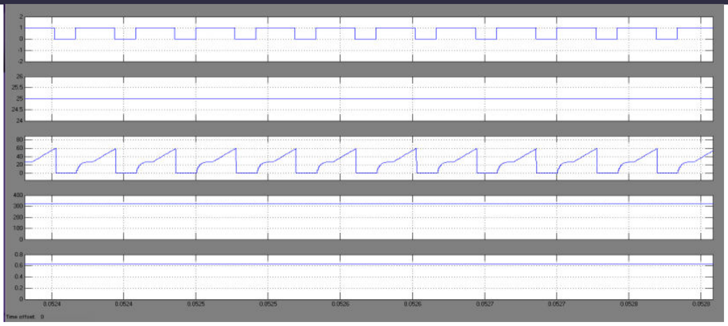

Fig.5 shows the simulation waveforms of proposed converter at N=4, m=2 conditions showing input voltage, current and output voltage, current

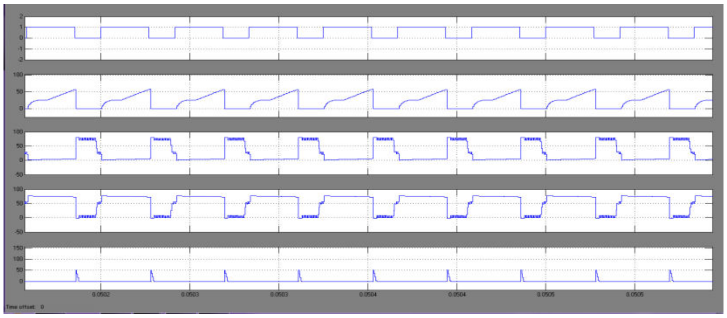

Fig.6 shows the simulation waveforms of proposed converter at N=4, m=2 conditions showing switch and diode voltage and current

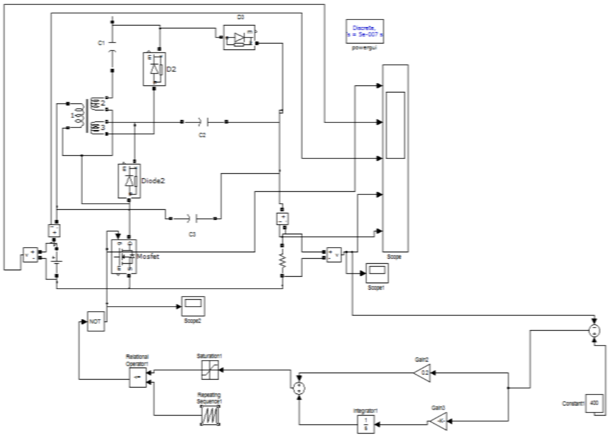

Fig.4 matlab/Simulink model of proposed converter in closed-loop method

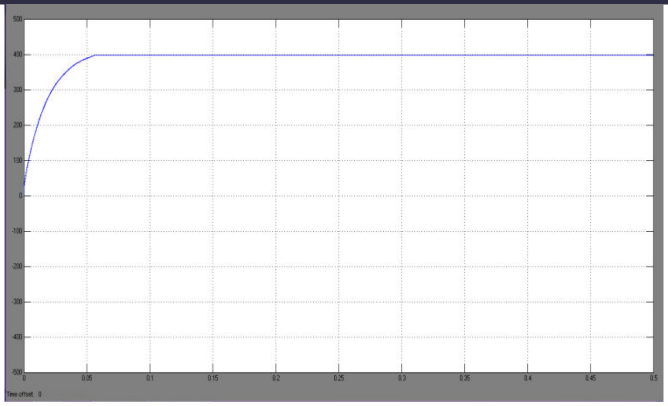

Fig.5 output voltage of the proposed converter in closed-loop condition

V. CONCLUSION

A high step-up dc/dc converter based on integrating coupled inductor and autotransformer is presented in this paper. The energy stored in the leakage inductance of the coupled inductor is recycled by using switched capacitors. The voltage stress across the main switch is reduced. Here the gate signals are generated using PWM control schemes. At last a same converter is controlled by closed loop PI control strategy with good dynamic response and low steady state error value with high stability factor.

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