A Novel High Efficiency High Step-up Interleaved Converter with Voltage Multiplier Circuit for a PV System

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Abstract- A high step-up converter is proposed for a photovoltaic system. A voltage multiplier used here provides high voltage gain without extreme duty cycle. The voltage multiplier is composed of a conventional boost converter and coupled inductors. An extra conventional boost converter is integrated into the first phase to achieve a considerably higher voltage conversion ratio. The two-phase configuration not only reduces the current stress through each power switch, but also constrains the input current ripple, which decreases the conduction losses of metal–oxide–semiconductor field-effect transistors (MOSFETs). It also functions as a clamp circuit which alleviates the voltage spikes across the power switches. So, the low-voltage-rated MOSFETs can be adopted for reductions of conduction losses and cost. Efficiency improves because the energy stored in leakage inductances is recycled to the output terminal.

Keywords- Boost–Fly back converter, High step-up, photovoltaic system, Voltage multiplier module.

I.   INTRODUCTION

Renewable sources of energy are increasingly valued worldwide because of energy shortage and environmental contamination. Renewable energy systems generate low voltage output and thus, high step-up dc/dc converters are widely employed in many renewable energy applications, including fuel cells, wind power, and photovoltaic systems are expected to pay an important role in future energy production. Such system transform light energy into electrical energy, and convert low voltage into high voltage via a step-up converter, which can convert energy into electricity using a grid-by-grid inverter or store energy into a battery set. Figure 1 shows a typical photovoltaic system that consists of a solar module, a high step up converter, a charge-discharge controller, a battery set, and an inverter.
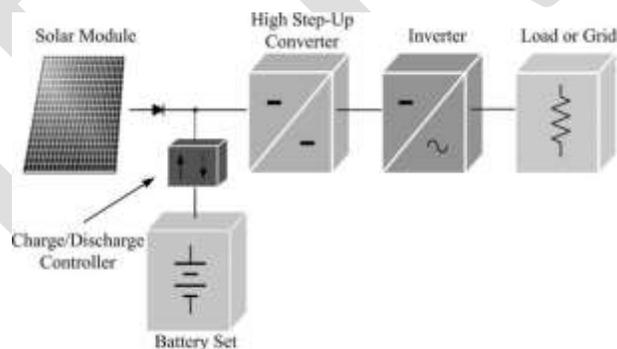

Figure 1: Typical Photovoltaic System

Conventional step-up converters, such as the boost converter and flyback converter, cannot achieve a high step-up conversion with high efficiency because of the resistances of elements or leakage inductance. Thus, a modified boost-flyback converter was proposed. Modifying a boost-fly back converter, shown in Figure 2(a) is one of the simple approaches step-up gain and the gain is realized via a coupled inductor. The performance of the converter is similar to an active-clamped flyback converter; thus, the leakage energy is recovered to the output terminal. An interleaved boost converter with a voltage-lift capacitor shown in Figure 2(b) is highly similar to the conventional interleaved type. It obtains extra voltage gain through the voltage-lift capacitor, and reduces the input current ripple, which is suitable for power factor correction (PFC) and high-power applications.
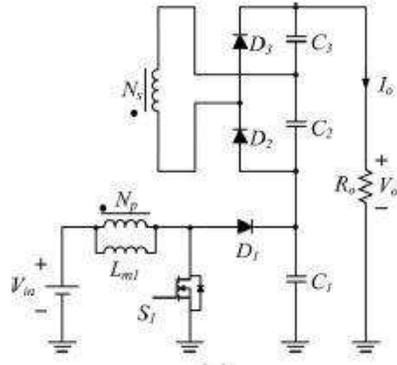
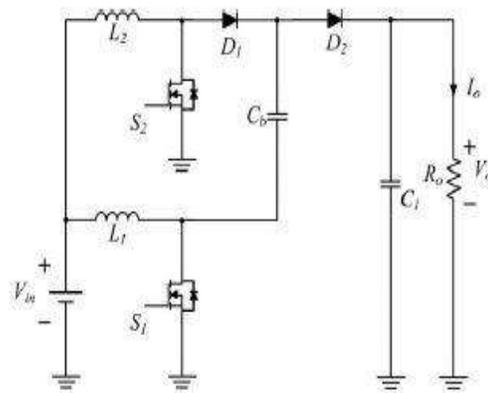**Figure 2(a): Modified Boost Flyback Converter**

Figure 2(b): Interleaved Boost Converter with a Voltage-lift Capacitor Structure

II. PROPOSED TOPOLOGY

In this paper, an asymmetrical interleaved high step-up converter that combines the advantages of the aforementioned converters is proposed, which combined the advantages of both. In the voltage multiplier module of the proposed converter, the turns ratio of coupled inductors can be designed to extend voltage gain, and a voltage-lift capacitor offers an extra voltage conversion ratio. The advantages of the proposed converter are as follows:

1) The converter is characterized by a low input current ripple and low conduction losses, making it suitable for high power applications;
2) The converter achieves the high step-up voltage gain that renewable energy systems require;
3) Leakage energy is recycled and sent to the output terminal, and alleviates large voltage spikes on the main switch;
4) The main switch voltage stress of the converter is substantially lower than of the output voltage.
5) Low cost and high efficiency are achieved.

A. Circuit Description

The proposed high step-up converter with voltage multiplier module is shown in Figure 3(a). A conventional boost converter and two coupled inductors are located in the voltage multiplier module, which is stacked on a boost converter to form an asymmetrical interleaved structure. Primary windings of the coupled inductors with N_p turns are employed to decrease input current ripple, and secondary windings of the coupled inductors with N_s turns are connected in series to extend voltage gain. The turns ratios of the coupled inductors are the same. The coupling references of the inductors are denoted by "." and "∗".
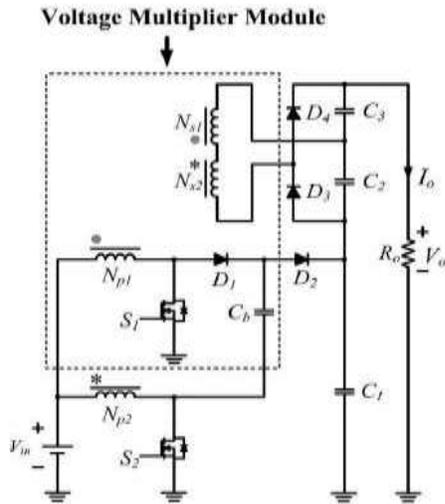
**Figure 3(a): Proposed High Step-up Converter with a Voltage Multiplier Module**

The equivalent circuit of the proposed converter is shown in Figure 3(b), where L_{m1} and L_{m2} are the magnetizing inductors, L_{k1} and L_{k2} represent the leakage inductors, S_1 and S_2 denote the power switches, C_b is the voltage-lift capacitor, and n is defined as a turns ratio N_s/N_p.
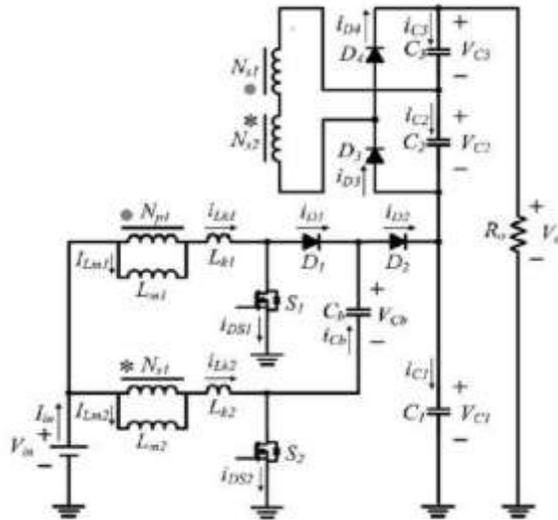

Figure 3(b): Equivalent Circuit

III. MODAL ANALYSIS

The proposed converter operates in continuous conduction mode (CCM), and the duty cycles of the power switches during steady operation are interleaved with a 180° phase shift and the duty cycles are greater than 0.5. The key steady waveforms in one switching period of the proposed converter contain six modes.
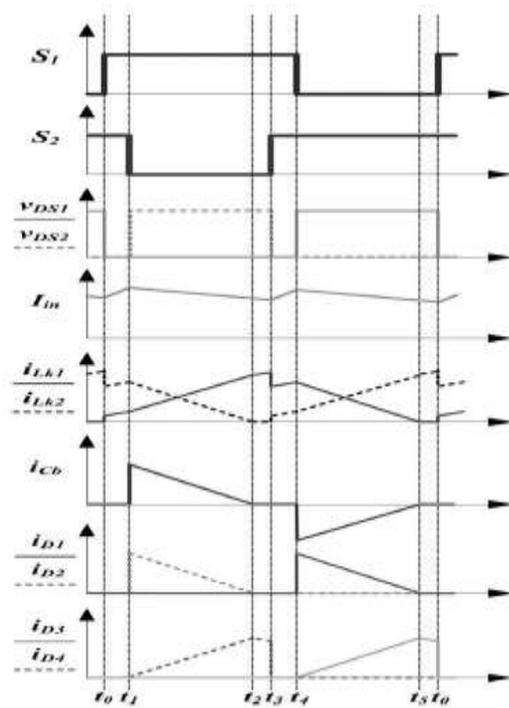
Figure 4: Steady Waveforms of the Proposed Converter

Mode 1[t_0, t_1]: At $t = t_0$, the power switches S_1 and S_2 are both turned ON. All of the diodes are reverse-biased. Magnetizing inductors L_{m1} and L_{m2} as well as leakage inductors L_{k1} and L_{k2} are linearly charged by the input voltage source $V_{in.}$
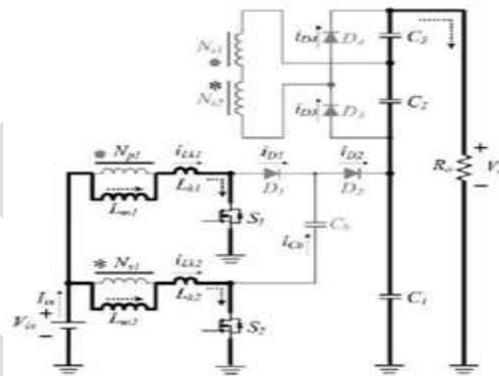
Figure 5(a): Mode 1

Mode 2[t_1, t_2]: At $t = t_1$, the power switches S_2 is switched OFF, thereby turned ON diodes D_2 and D_4. The energy that magnetizing inductor L_{m2} has stored is transferred to the secondary side charging the output filter capacitor C_3. The input voltage source, magnetizing inductor L_{m2}, leakage inductor L_{k2}, and voltage-lift capacitor C_b release energy to the output filter capacitor C_1 via diode D_2, thereby extending the voltage on C_1.
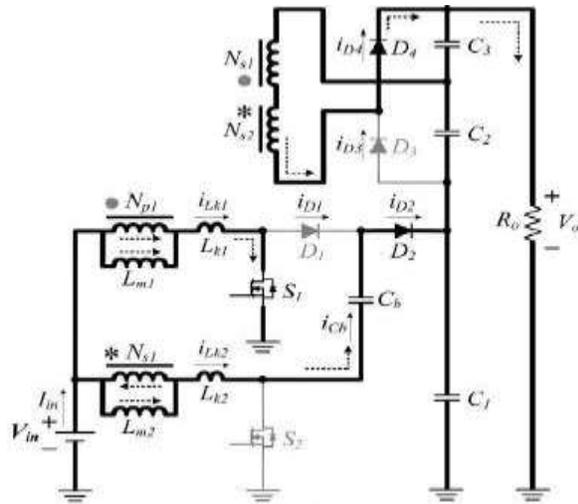
Figure 5(b): Mode 2

Mode 3[t_2, t_3]: At $t = t_2$, diode D_2 automatically switches OFF because the total energy of leakage inductor L_{k2} has been completely released to the output filter capacitor C_1. Magnetizing inductor L_{m2} transfers energy to the secondary side charging the output filter capacitor C_3 via diode D_4 until t_3.
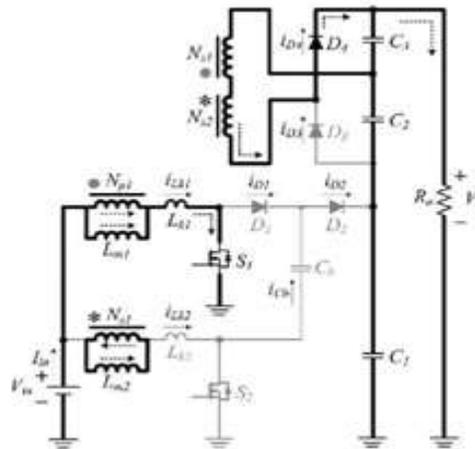

Figure 5(c): Mode 3

Mode 4[t_3, t_4]: At $t = t_3$, the power switch S_2 is switched ON and all the diodes are turned OFF. The operating states of modes 1 and 4 are similar.
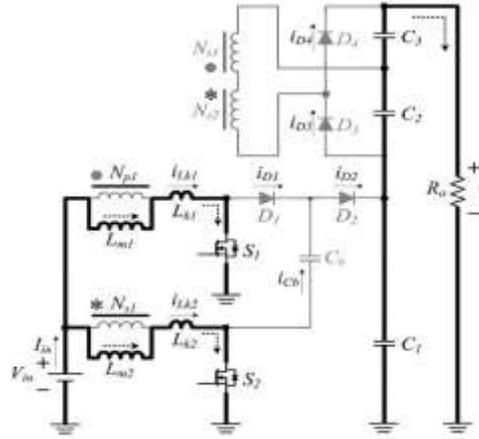
Figure 5(d): Mode 4

Mode 5[t_4, t_5]: At $t = t_4$, the power switch S_1 is switched OFF which turns ON diodes D_1 and D_3. The energy stored in magnetizing inductor L_{m1} is transferred to secondary side charging the output filter capacitor C_2. The input voltage source and magnetizing inductor L_{m1} release energy to voltage-lift capacitor C_b via diode D_1, which stores extra energy in C_b.
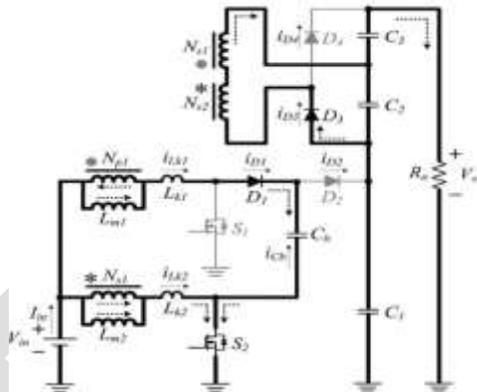

Figure 5(e): Mode 5

Mode 6[t_5, t_0]: At $t = t_5$, diode D_1 is automatically turned OFF because the total energy of leakage inductor L_{k1} has been completely released to voltage-lift capacitor C_b. Magnetizing inductor L_{m1} transfers energy to the secondary side charging the output filter capacitor C_2 via diode D_3 until t_0.
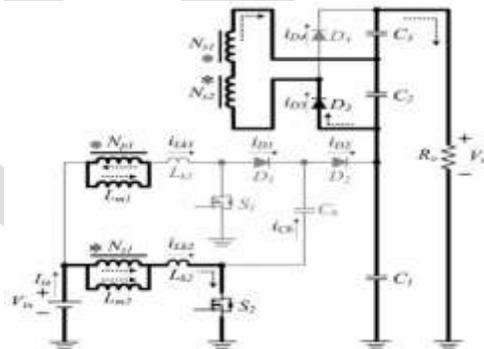

Figure 5(f): Mode 6

IV. STEADY STATE ANALYSIS

The transient characteristics of circuitry are disregarded to simplify the circuit performance analysis of the proposed converter in CCM, and some formulated assumptions are as follows:

1) All of the components in the proposed converter are ideal;
2) Leakage inductors L_{k1} and L_{k2} are neglected.
3) Voltage V_{cb}, V_{c1}, V_{c2}, and V_{c3} are considered to be constant because of infinitely large capacitance.

A. Voltage Gain

The first-phase converter can be regarded as a conventional boost converter, thus voltage V_{cb} can be derived from:

$$V_{cb} = V_{in} \frac{1}{1-D} \quad \text{------ (1)}$$

When switch S_1 is turned ON and switch S_2 is turned OFF, voltage V_{C1} can be derived from:

$$V_{C1} = \frac{1}{1-D} V_{in} + V_{cb} = \frac{2}{1-D} V_{in} \quad \text{-------- (2)}$$

The output filter capacitors C_2 and C_3 are charged by energy transformation from the primary side. When S_2 is in turn-on state and S_1 is in turn-off state, V_{C2} is equal to induced voltage of N_{s1} plus induced voltage of N_{s2}, and when S_1 is in turn-on state and S_2 is in turn-off state, V_{C3} is also equal to induced voltage of N_{s1} plus induced voltage of N_{s2}. Thus, voltages V_{c2} and V_{c3} can be derived from

$$V_{c2} = V_{c3} = nV_{in}\left(1 + \frac{D}{1-D}\right) = \frac{n}{1-D} V_{in} \quad \text{--------- (3)}$$

The output voltage can be derived from:

$$V_o = V_{c1} + V_{c2} + V_{c3} = \frac{2n+2}{1-D} V_{in} \quad \text{------- (4)}$$

The voltage gain of the proposed converter is

$$\frac{V_o}{V_{in}} = \frac{2n+2}{1-D} \quad \text{--------- (5)}$$

Above equation confirms that the proposed converter has a high step-up voltage gain without an extreme duty cycle.

B. Voltage Stresses on Semi Conductor Components

The voltage ripples on the capacitors are ignored to simplify the voltage stress analyses of the components of the proposed converter.

The voltage stresses on power switches S_1 and S_2 are derived from:

$$V_{s1} = V_{s2} = \frac{1}{1-D} V_{in} \quad \text{--------- (6)}$$

The voltage stresses on power switches S_1 and S_2 related to the output voltage V_o and the turns ratio n can be expressed as:

$$V_{s1} = V_{s2} = V_o - \frac{2n+1}{1-D} V_{in} \quad \text{----------- (7)}$$

The voltage stresses on the power switches account for half of output voltage V_o, even if turns ratio n is 0. The voltage stress on D_1 is equal to V_{C1}, and the voltage stress on diode D_2 is voltage $V_{C1} - V_{cb}$. These voltage stresses can be derived from:

$$V_{D1} = V_{C1} = \frac{2}{1-D} V_{in} \quad \text{--------- (8)}$$

$$V_{D2} = V_{C1} - V_{cb} = \frac{1}{1-D} V_{in} \quad \text{--------- (9)}$$

The voltage stressed on the diodes D_1 and D_2 and D_3 and D_4 related to the output voltage V_o and the turns ratio n can be expressed as:

$$V_{D1} = V_o - \frac{2n}{1-D} V_{in} \quad \text{--------- (10)} \qquad\qquad V_{D3} = V_{D4} = V_o - \frac{2}{1-D} V_{in} \text{---------- (12)}$$

$$V_{D2} = V_o V_{in} = \frac{2}{1-D} \quad \text{------- (11)}$$

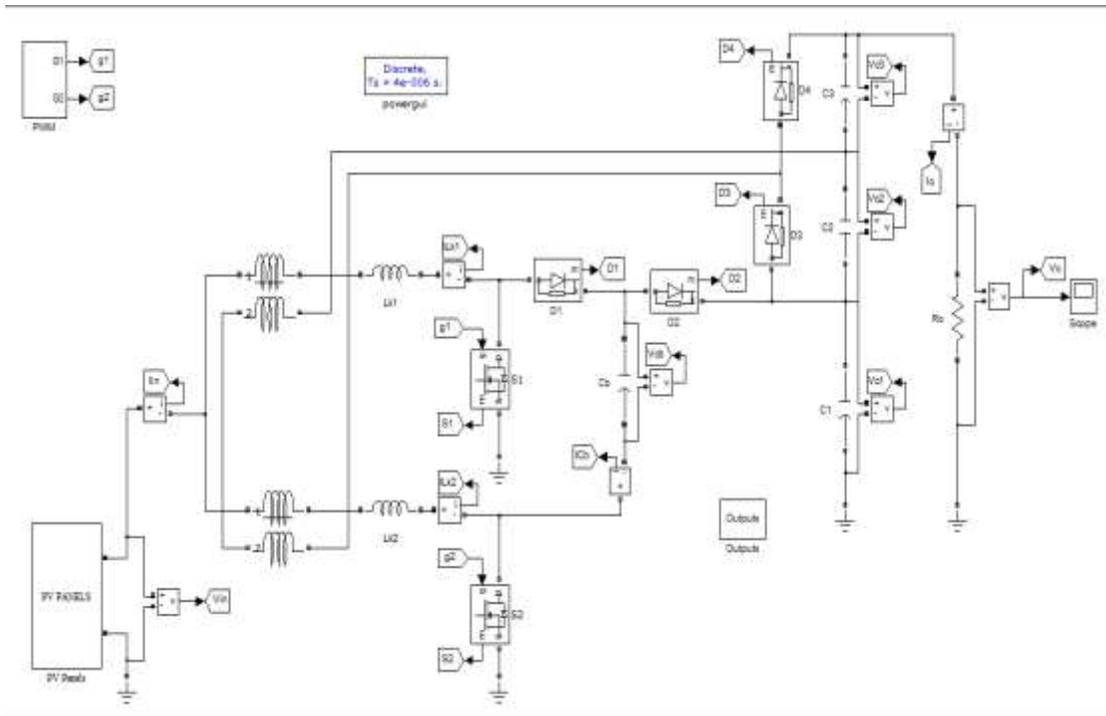## V. MATLAB SIMULATION DIAGRAM

Figure 6: Simulation Diagram

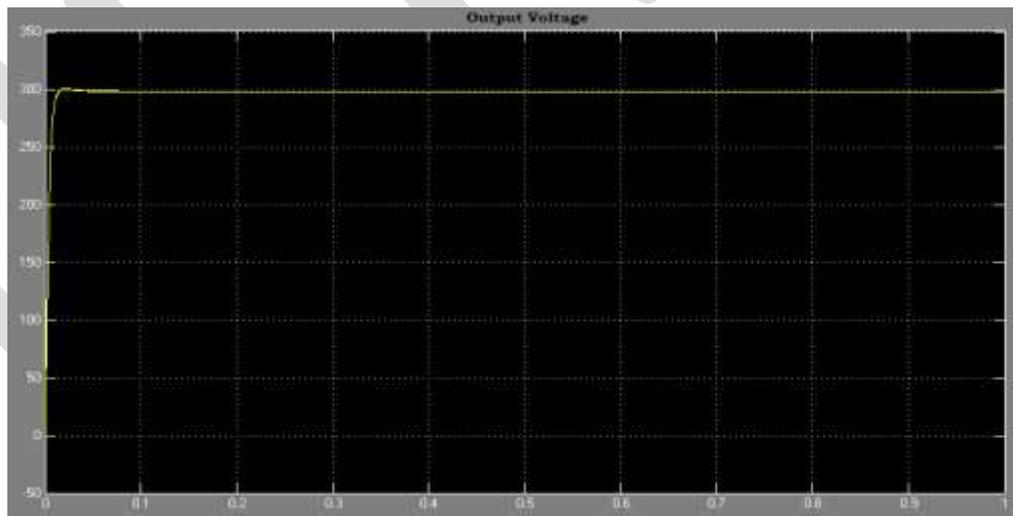## VI. MEASURED WAVEFORMS
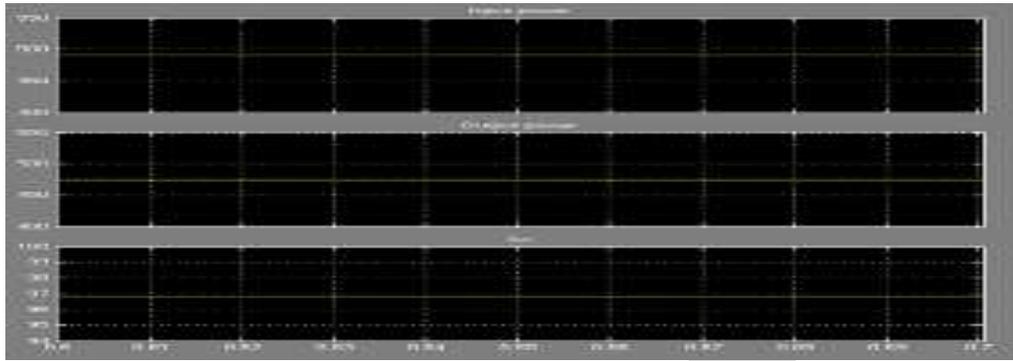

Figure 7(a): output voltage

Figure 7(b): input and output power and efficiency
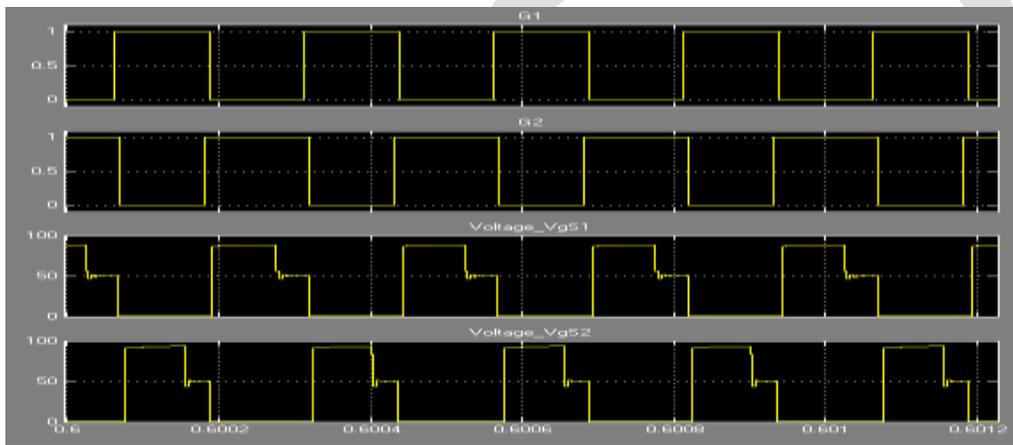

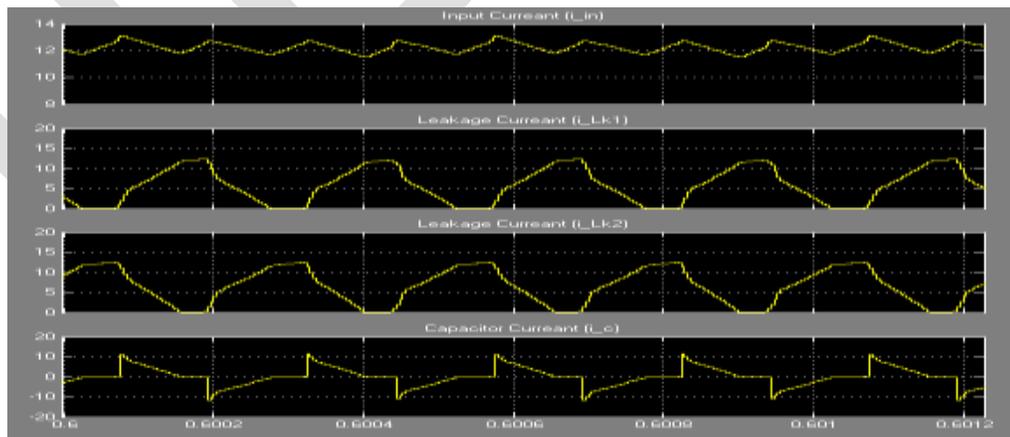**Figure 7(c): Measured $V_{g1} and V_{g2}$ waveforms**

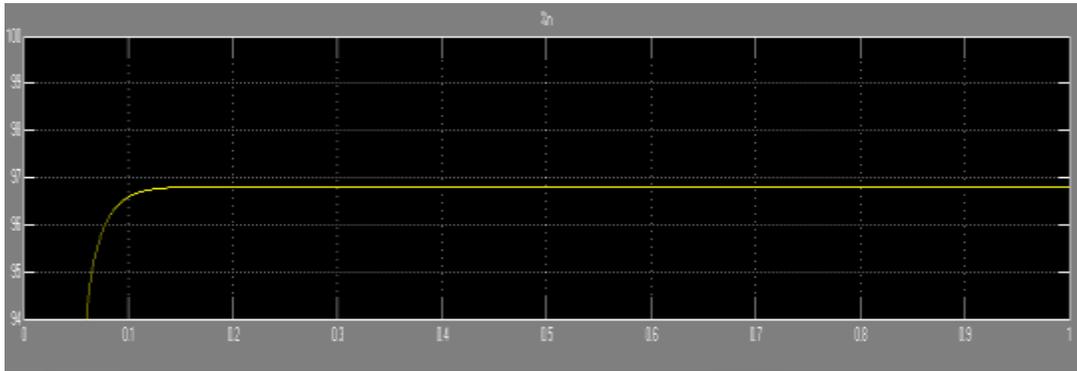**Figure 7(d): measured current wave forms**

Figure 7(e): Measured output efficiency

VII. PROPOSED CONCEPT

The proposed high step-up interleaved converter with a voltage multiplier module is shown in Figure 2. The voltage multiplier module is composed of two coupled inductors and two switched capacitors and is inserted between a conventional interleaved boost converter to form a modified boost-flyback-forward interleaved structure. When the switches turn off by turn, the phase whose switch is in OFF state performs as a flyback converter, and the other phase whose switch is in ON state performs as a forward converter.

Primary windings of the coupled inductors with N_p turns are employed to decrease input current ripple, and secondary windings of the coupled inductors with N_s turns are connected in series to extend voltage gain. The turn ratios of the coupled inductors are the same. The coupling references of the inductors are denoted by "." and "$*$".
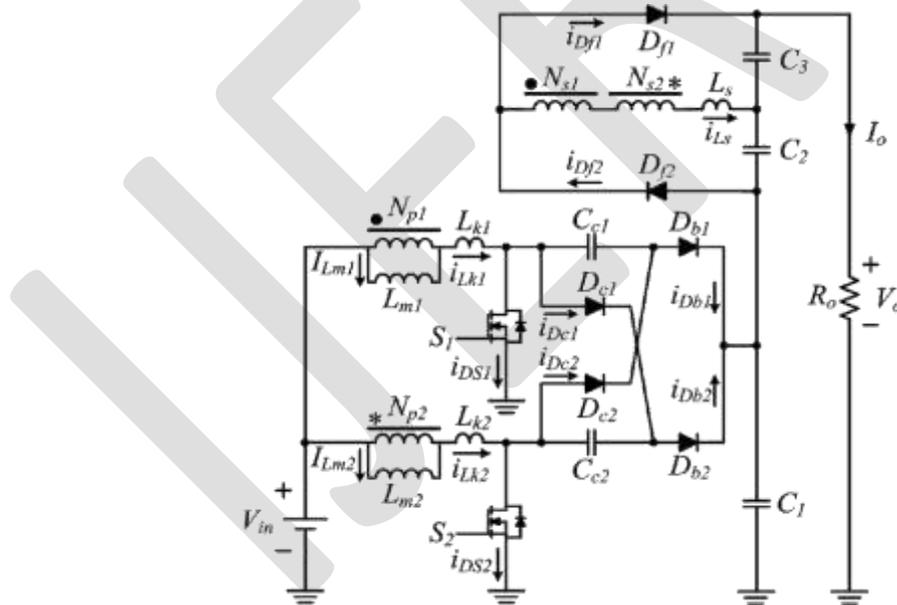

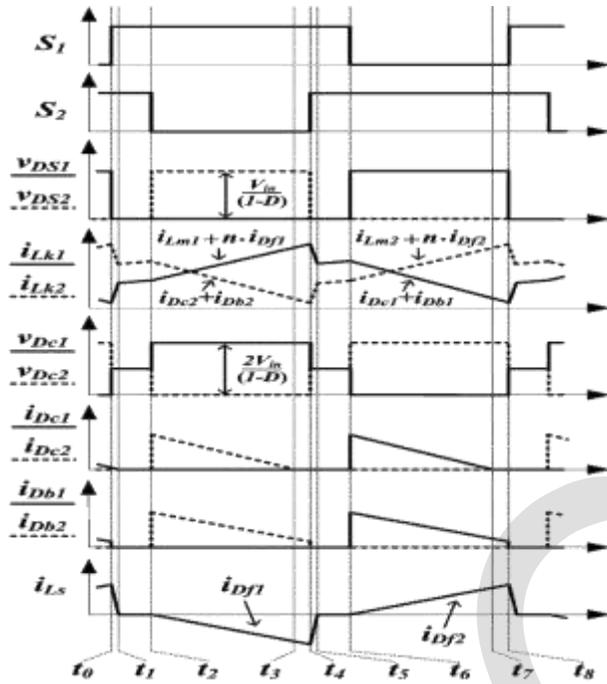**Figure 8: Equivalent Circuit of the Proposed Converter**

Figure 9: Steady Waveform of the Proposed Converter in CCM

VIII. PROPOSED STEADY-STATE ANALYSIS

The transient characteristics of circuitry are disregarded to simplify the circuit performance analysis of the proposed converter in CCM, and some formulated assumptions are as follows:

1) All of the components in the proposed converter are ideal.
2) Leakage inductors L_{k1}, L_{k2}, and L_s are neglected.
3) Voltages on all capacitors are considered to be constant because of infinitely large capacitance.
4) Due to the completely symmetrical interleaved structure, the related components are defined as the corresponding symbols such as D_{c1} and D_{c2} defined as DC.

A. Step-up Gain

The voltage on clamp capacitor C_C can be regarded as an output voltage of the boost converter; thus, voltage V_{Cc} can be derived from the equation.

$$V_{cc} = \frac{1}{1-D} V_{in} \text{----------- (1)}$$

When one of the switches turns off, voltage V_{C1} can obtain a double output voltage of the boost converter derived from the equation.

$$V_{c1} = \frac{1}{1-D} V_{in} + V_{cc} = \frac{2}{1-D} V_{in} \text{----------- (2)}$$

The output filter capacitors C_2 and C_3 are charged by energy transformation from the primary side. When S_2 is in ON state and S_1 is in OFF state, V_{C2} is equal to the sum of the induced voltage of N_{S1} and the induced voltage of N_{S2}, and when S_1 is in ON state and S_2 is in OFF state, V_{C3} is also equal to the sum of the induced voltage of N_{S1} and the induced voltage of N_{S2}. Thus, voltages V_{C2} and V_{C3} can be derived from:

$$V_{c2} = V_{c3} = nV_{in} \left(1 + \frac{D}{1-D}\right) = \frac{n}{1-D} V_{in} \text{----------- (3)}$$

The output voltage can be derived from:

$$V_o = V_{c1} + V_{c2} + V_{c3} = \frac{2n+2}{1-D} V_{in} \text{------------ (4)}$$

In addition, the voltage gain of the proposed converter is

$$\frac{V_o}{V_{in}} = \frac{2n+2}{1-D} \text{----------- (5)}$$

B. *Voltage Stresses on Semi Conductor Components*

Voltage ripple on capacitor was ignored to simplify the voltage stress analysis of the components of the proposed converter. The voltage stress on power switch S was clamped and derived from

$$V_{s1} = V_{s2} = \frac{2}{1-D}V_{in} = \frac{1}{2n+2}V_o \text{ ----------- (6)}$$

The voltage stress can be derived from

$$V_{dc1} = V_{dc2} = \frac{2}{1-D}V_{in} = \frac{1}{n+1}V_o \text{ ------------- (7)}$$

IX. DESIGN AND EXPERIMENT OF PROPOSED CONVERTER

A 0.5 kW prototype of the proposed high step-up converter is tested. The electrical specifications are $V_{in} = 40\,V$, $V_o = 300\,V$ and $f_s = 40\,kHz$. The major components have been chosen as follows: Magnetizing inductors L_{m1} and $L_{m2} = 133\mu H$; turn ratio $n = 1$; power switches S_1 and S_2 are IRFP4227; diodes D_{c1} and D_{c2} are BYQ28E-200; diodes D_{b1}, D_{b2}, D_{f1} and D_{f2} are FCF06A-40; capacitors C_{c1}, C_{c2}, C_2 and $C_3 = 220\mu F$; and $C_1 = 470 Mf$.

Design Parameters

PARAMETER	VALUE
Input Voltage	40 V DC
Output Voltage	380 V DC
Switching Frequency	40 KHz
Magnetizing Inductors (L_{m1} & L_{m2})	133 μH
Capacitors (C_{c1}, C_{c2}, C_2 & C_3)	220 μF
Capacitor (C_1)	470 μF
Output Power	500 W

The design consideration of the proposed converter includes component selection and coupled inductor design, which are based on the analysis present in the previous section. In the proposed converter, the values of primary leakage inductor of coupled inductors set as close as possible for current sharing performance and the leakage inductors L_{k1} and L_{k2} are 1.6 μH. Due to the performance of high step-up gain, the turn ratio n can be set as one for the prototype circuit with 40 V input voltage and 380 V output voltage to reduce cost, volume and conduction loss of winding. Thus, copper resistance which affect efficiency much can be decreased.
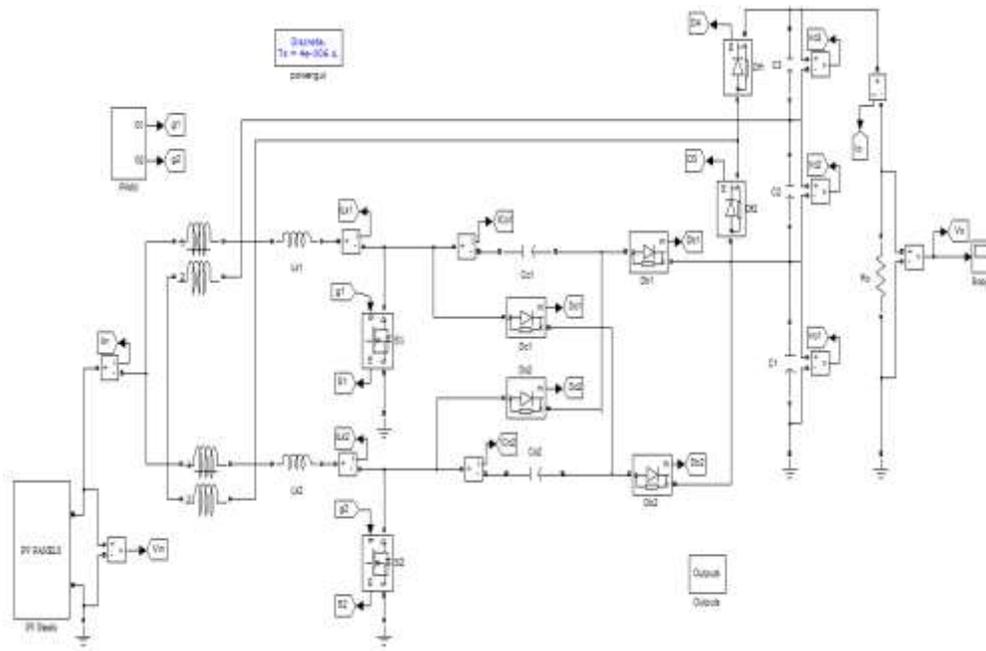
X. MATLAB SIMULATION DIAGRAM

Figure 10: Simulation diagram
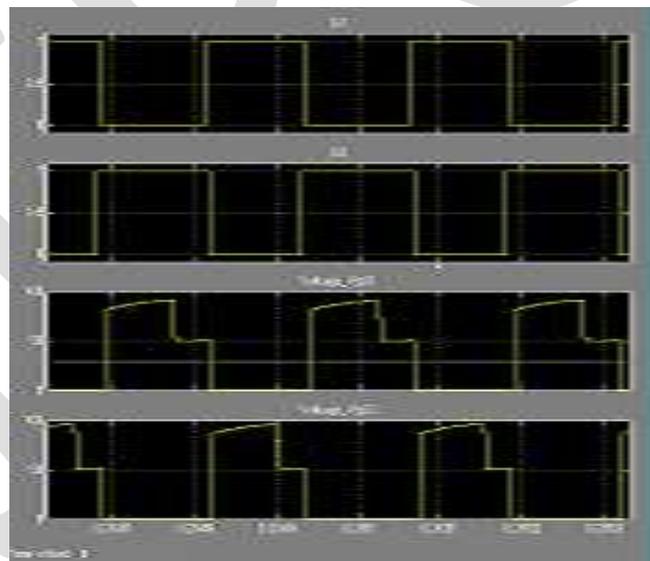
XI.   MEASURED WAVEFORMS

Figure 11(a): gate pulse and $V_{gs1} and V_{gs2}$ **measured wave forms**
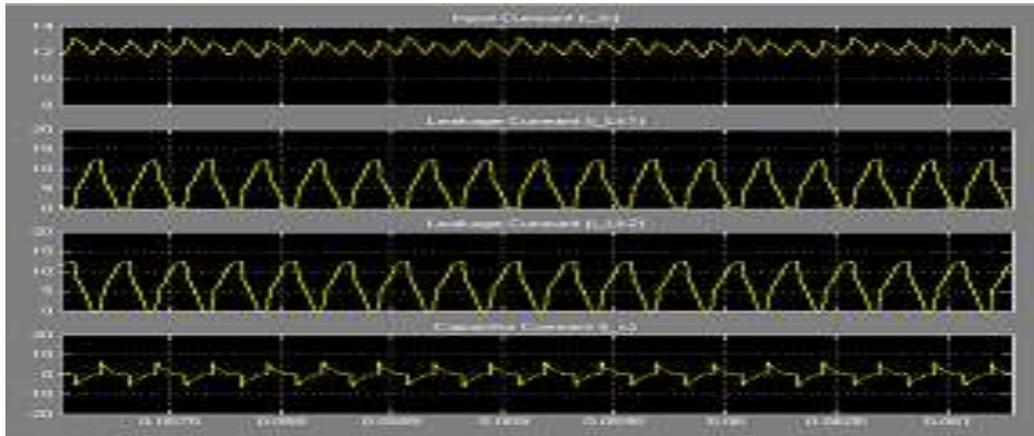
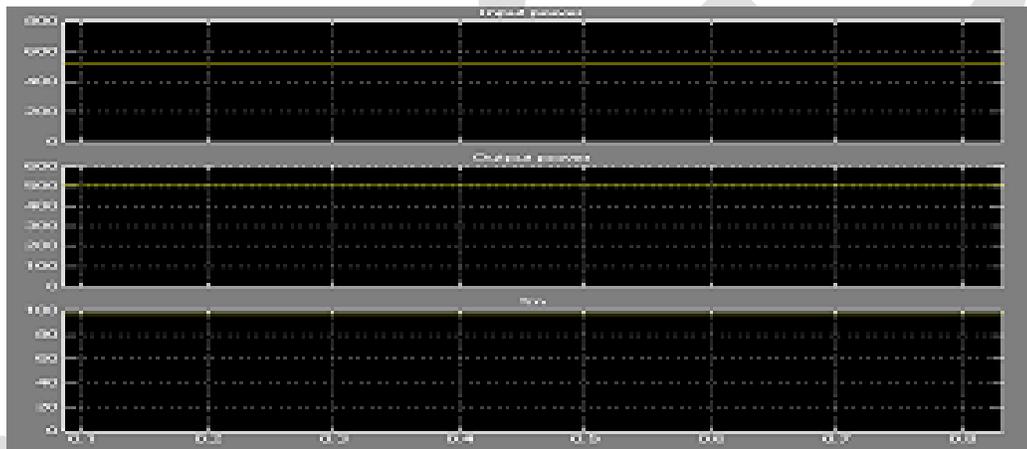**Figure 11(b): Measured current wave forms**

Figure 11(c): input and output power and efficiency waveforms
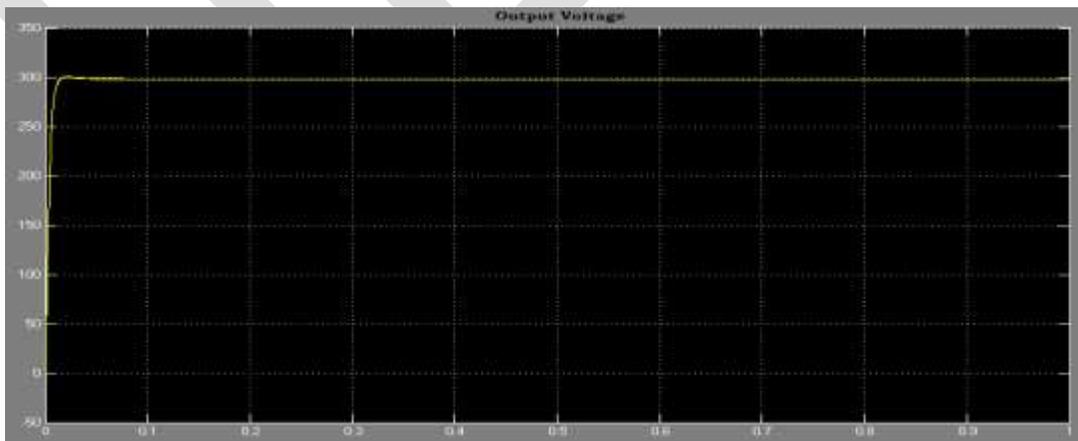

Figure 11(d): Measured output voltage

XII. CONCLUSION

This paper has presented the theoretical analysis of steady state, related consideration, simulation results for the proposed converter. The proposed converter has successfully implemented an efficient high step-up conversion through the voltage multiplier module. The interleaved structure reduces the input current ripple and distributes the current through each component. In addition, the lossless passive clamp function recycles the leakage energy and constrains a large voltage spike across the power switch. Meanwhile, the voltage stress on the power switch is restricted and much lower than the output voltage (300 V). Furthermore, the full-load efficiency is 96.4% at $P_o = 500\ W$, and the highest efficiency is 97.7%.Thus, the proposed converter is suitable for high-power or renewable energy applications that need high step-up conversion.

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