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A NOVEL ON HIGH STEP UP VOLTAGE BY USING VOLTAGE MULTIPLIER MODULE WITH PI CONTROLLER

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ABSTRACT

A novel high step-up converter, which is suitable for renewable energy system, is proposed in this paper. Through a voltage multiplier module composed of switched capacitors, coupled inductors and PI controller, a conventional interleaved boost converter obtains high step-up gain without operating at extreme duty ratio. The configuration of the proposed converter not only reduces the current stress but also constrains the input current ripple, which decreases the conduction losses and lengthens the lifetime of the input source. In addition, due to the lossless passive clamp performance, leakage energy is recycled to the output terminal. Hence, large voltage spikes across the main switches are alleviated, and the efficiency is improved. Even the low voltage stress makes the low-voltage-rated MOSFETs be adopted for reductions of conduction losses and cost. Finally, the prototype circuit with 40-V input voltage, 550-V output, and 2250-W output power is operated to verify its performance.

***Keywords*: Boost-flyback converter, high step-up, photo- voltaic (PV) system, voltage multiplier module, PI controller.**

I. INTRODUCTION

NOWADAYS, renewable energy is increasingly valued and employed worldwide because ofenergyshortage and environmental contamination [1]. Renewable energy systems generate low voltage output, and thus, high step-up dc/dc converters have been widely employed in many renewable energy applications such fuel cells, wind power generation, and photovoltaic (PV) systems. Such systems transform energy from renewable sources 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 dc micro grid. Fig. 1 shows a typical renewable energy system that consists of renewable energy sources, a step-up converter, and an inverter for ac application. The high step-up conversion may require two-stage converters with cascade structure for enough step-up gain, which decreases the efficiency and increases the cost. Thus, a high step-up converter is seen as an important stage in the system because such a system requires a sufficiently high step-up conversion with high efficiency.

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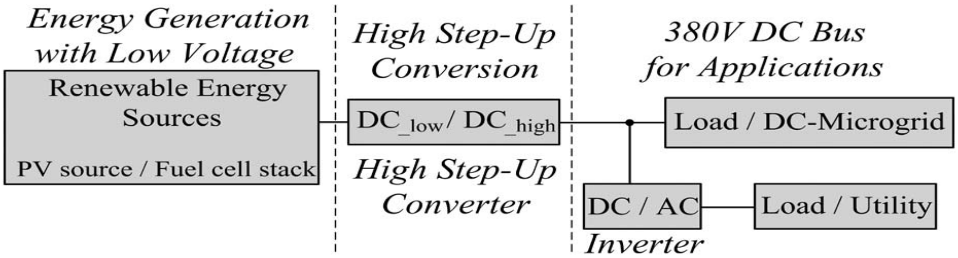
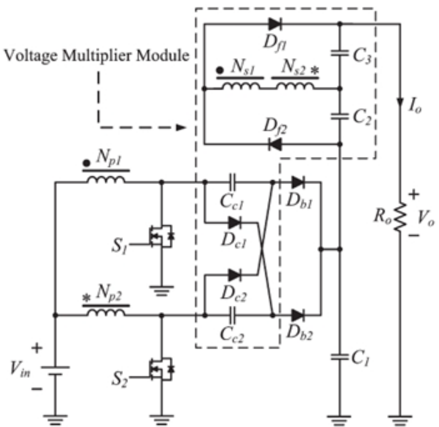


Fig.1.Typical renewable energy system

Theoretically, 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; also, the voltage stresses are large.Thus, in recent years, many novel high step- up converters have been developed [2]. Despite these advances, high step-up single-switch converters are unsuitable to operate at heavy load given a large input current ripple, which increases conduction losses.. The conventional interleaved boost converter is an excellent candidate for high-power applications and power factor correction.Unfortunately, the step-up gain is limited, and the voltage stresses on semiconductor componentsare equal to output voltage.Hence, based on the aforementioned considerations, modifying a conventional interleavedboost converter for high step-up and high-power application is a suitable approach.To integrate switched capacitors into an interleaved boost converter may make voltage gain reduplicate, but no employment of coupled inductors causes the step-up voltage gain to be limited [3].Oppositely, to integrate only coupled inductors into an interleaved boost converter may make voltage gain higher and adjustable, but no employment of switched capacitors causes the step-up voltage gain to be ordinary [4],[5]. Thus, the synchronous employment of coupled inductors and switched capacitors is a better concept; moreover, high step-up gain, high efficiency, and low voltage stress are achieved even for high-power applications [6]-[7].

The proposed converter is a conventional interleaved boost converter integrated with a voltage multiplier module, and the voltage multiplier module is composed of switched capacitors and coupled inductors. The coupled inductors can be designed to extend step-up gain, and the switched capacitors offer extra voltage conversion ratio. In addition, when one of the switches turns off, the energy stored in the magnetizing inductor will transfer via three respective paths; thus, the current distribution not only decreases the conduction losses by lower effective current but also makes currents through some diodes decrease to zero before they turn off, which alleviate diode reverse recovery losses.



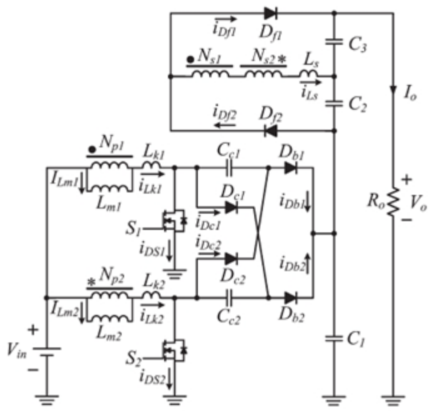


Fig.2.Proposed high step-up converter **Fig.3.Equivalent circuit of the proposed converter**

The advantages of the proposed converter are as follows.

1) The proposed converter is characterized by low input current ripple and low conduction losses, which increases the lifetime of renewable energy sources and makes it suitable for high-power applications.

2) The converter achieves the high step-up gain that renewable energy systems require.

3) Due to the lossless passive clamp performance, leakage energy is recycled to the output terminal. Hence, large voltage spikes across the main switches are alleviated, and the efficiency is improved.

4) Low cost and high efficiency are achieved by employment of the low-voltage-rated power switch with low$R_{DS}(ON)$; also, the voltage stresses on main switches and diodes are substantially lower than output voltage.

5) The inherent configuration of the proposed converter makes some diodes decrease conduction losses and alleviate diode reverse recovery losses.

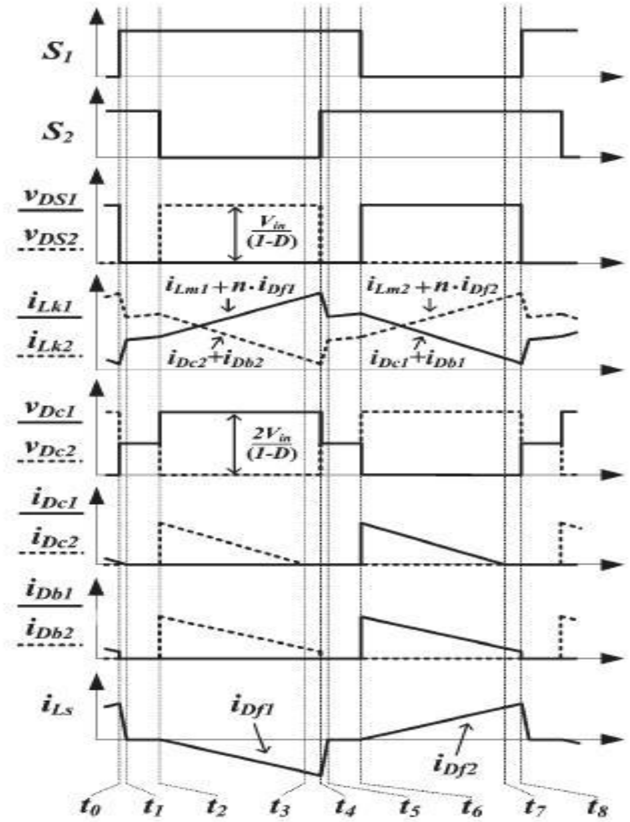


Fig.4.Steady waveform of the proposed converter in CCM.

II. OPERATING PRINCIPLES

The proposed high step-up interleaved converter with a voltage multiplier module is shown in Fig. 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 withN_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 "*".

The equivalent circuit of the proposed converter is shown in Fig. 3, where L_{m1} and L_{m2} are the magnetizing inductors; L_{k1} and L_{k2} represent the leakage inductors; L_S represents the series leakage inductors in the secondary side; S_1 and S_2 denote the power switches; C_{c1} and C_{c2} are the switched capacitors; and C_1, C_2 and C_3 are the output capacitors. D_{C1} and D_{C2} are the clamp diodes, D_{b1} and D_{b2} represent the output diodes for boost operation with switched capacitors, D_{f1} and D_{f2} represent the output diodes for flyback-forward operation, and *n* is defined as turn ratio N_s/N_p. In the circuit analysis, the proposed converter operates in Continuous conduction mode (CCM), and the duty cycles of the power switches during steady operation are greater than 0.5 and are interleaved with a 180° phase shift. The key steady waveform in one switching period of the proposed converter contains six modes, which are depicted in Fig. 4, and Fig. 5 shows the topological stages of the circuit.

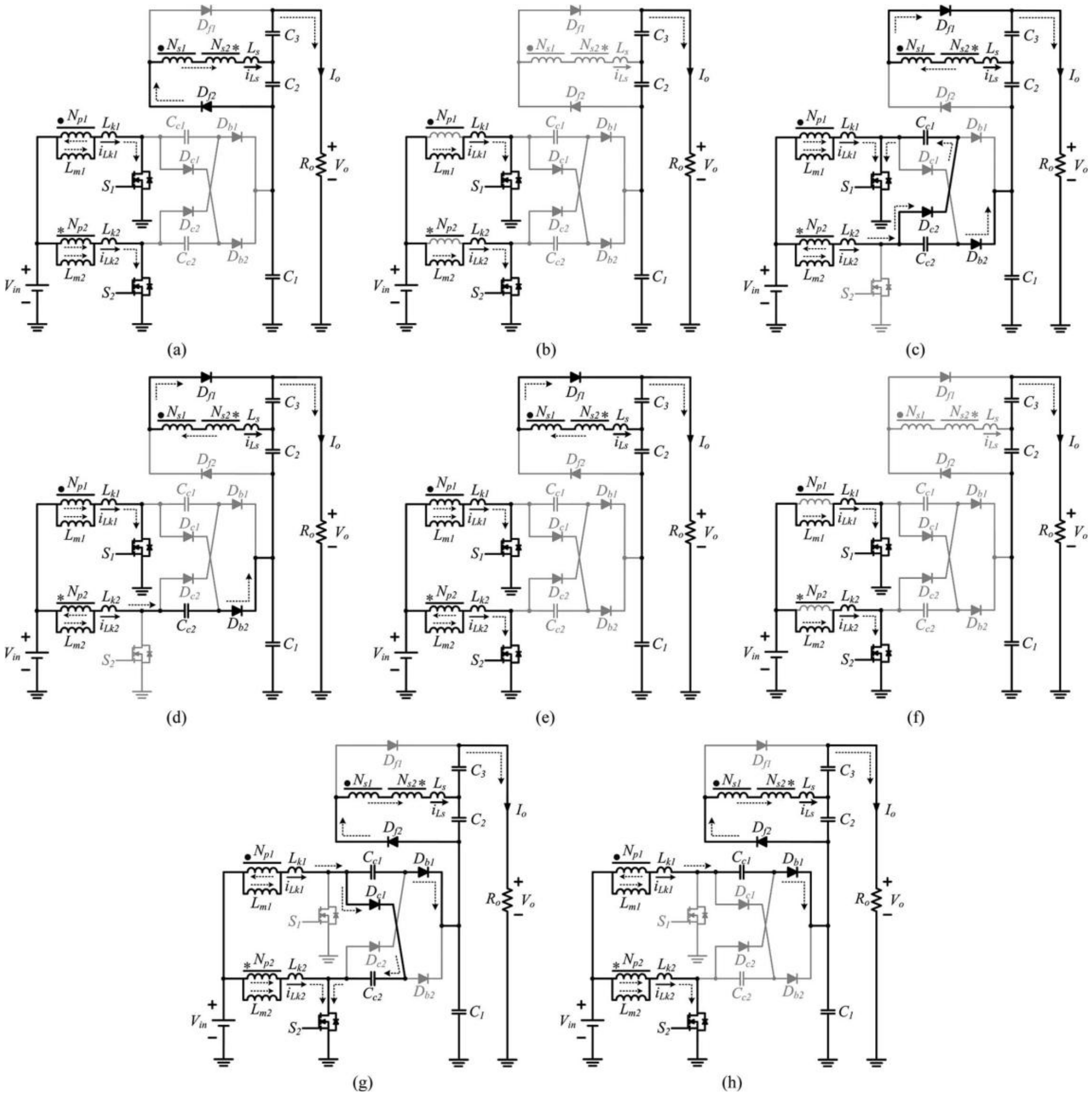


Fig.5.Operating modes of the proposed converter. (a) Mode I [t_o, t_1]. (b) Mode II [t_1, t_2]. (c) Mode III [t_2, t_3]. (d) Mode IV [t_3, t_4]. (e) Mode V [t_4, t_5]. (f) Mode VI [t_5, t_6]. (g) Mode VII [t_6, t_7]. (h) Mode VIII [t_7, t_8].

Mode I [t_o, t_1]*:* At t =t_0, the power switch S_2 remains in ON state, and the other power switchS_1 begins to turn on. The diodesD_{C1},D_{C2},D_{b1},D_{b2} andD_{f1} are reversed biased, as shown in Fig. 5(a). The series leakage inductors L_S quickly release the stored energy to the output terminal via flyback- forward diodeD_{f2} and the current through series leakage inductors L_S decreases to zero. Thus, the magnetizing inductor L_{m1} still transfers energy to the secondary side of coupled inductors.

The current through leakage inductorL_{K1}increases linearly and the other current through leakage inductorL_{k2} decreases linearly.

Mode II [t_1, t_2]*:* At t =t_1, both of the power switchesS_1andS_2 remain in ON state, and all diodes are reversed biased,as shown in Fig. 5(b). Both currents through leakage inductors L_{k1} andL_{k2} are increased linearly due to charging by input Voltage sourceV_{in}.

Mode III [t_2, t_3]*:* At t =t_2, the power switchS_1remains in ON state, and the other power switchS_2begins to turn off. The diodesD_{c1},D_{b1} andD_{f2} are reversed biased, as shown in Fig. 5(c). The energy stored in magnetizing inductorL_{m2} transfers to the secondary side of coupled inductors, and the current through series leakage inductors$L_s$flows to output capacitorC_3via flyback-forward diodeD_{f1}. The voltage stress on power switch$S_2$is clamped by clamp capacitorC_{C1} which equals the output voltage of the boost converter. The input volt-age source, magnetizing inductorL_{m2}, leakage inductorL_{k2}, and clamp capacitorC_{C2}release energy to the output terminal; thus,V_{C1} obtains a double output voltage of the boost converter.

Mode IV [t_3,t_4]*:* At t =t_3, the currenti_{DC2} has naturally decreased to zero due to the magnetizing current distribution, and hence, diode reverse recovery losses are alleviated and conduction losses are decreased. Both power switches and all diodes remain in previous states except the clamp diodeD_{C2}, as shown in Fig. 5(d).

Mode V [t_4,t_5]*:* At t =t_4, the power switchS_1 remains in ON state, and the other power switchS_2 begins to turn on. The diodesD_{C1},D_{C2},D_{b1},D_{b2}, andD_{f2} are reversedL_S quickly release the stored energy to the output terminal via flyback-forward diodeD_{f1}, and the current through series leakage inductors decreases to zero. Thus, the magnetizing inductorL_{m2} still transfers energy to the secondary side of Coupled inductors. The current through leakage inductorL_{k2} increases linearly, and the other current through leakage inductorL_{k1} decreases linearly.

Mode VI[t_5,t_6]*:* At t =t_5, both of the power switchesS_1andS_2 remain in ON state, and all diodes are reversed biased, as shown in Fig. 5(f). Both currents through leakage inductors L_{k1} andL_{k2} are increased linearly due to charging by input voltage sourceV_{in}.

Mode VII[t_6,t_7]*:* At t =t_6, the power switchS_2 remains in ON state, and the other power switchS_1 begins to turn off. The diodesD_{C2},D_{b2}, andD_{f1} are reversed biased, as shown in Fig. 5(g). The energy stored in magnetizing inductorL_{m1} transfers to the secondary side of coupled inductors, and the current through series leakage inductors flows to output capacitorC_2via flyback-forward diodeD_{f2}. The voltage stress on power switchS_1 is clamped by clamp capacitorC_{C2} which equals the output voltage of the boost converter. The input voltage source, magnetizing inductorL_{m1}, leakage inductorL_{k1}, and clamp capacitorC_{C1} release energy to the output terminal; thus,V_{C1} obtains double output voltage of the boost converter.

Mode VIII[t_7,t_8]: At t =t_7, the currenti_{DC1} has naturally decreased to zero due to the magnetizing current distribution, and hence, diode reverse recovery losses are alleviated and conduction losses are decreased. Both power switches and all diodes remain in previous states except the clamp diodeD_{C1}, as shown in Fig. 5(h).

III. 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 inductorsL_{k1},L_{k2}, andL_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 asD_{C1} andD_{C2} defined asD_C.

Step-Up Gain

The voltage on clamp capacitor$C_c$can be regarded as an output voltage of the boost converter; thus, voltageV_{Cc} can be derived from

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

When one of the switches turns off, voltageV_{c1} can obtain adouble output voltage of the boost converter derived from

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

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

$$V_{C2} = V_{C3} = n.V_{in}\left(1 + \frac{D}{1-D}\right) = \frac{n}{1-D} V_{in} \qquad (3)$$

The output voltage can be derived from

$$V_o = V_{c1} + V_{c2} + V_{C3} = \frac{2n+2}{1-D} V_{in} \qquad (4)$$

In addition, the voltage gain of the proposed converter is

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

Equation (5) confirms that the proposed converter has a highstep-up voltage gain without an extreme duty cycle. The curve

of the voltage gain related to turn ratio n and duty cycle. When the duty cycle is merely 0.6, the voltagegain reaches ten at a turn ratio n of one; the voltage gain reaches30 at a turn ratio n of five.

IV. DESIGN AND EXPERIMENT OF PROPOSED CONVERTER

A 1-kW prototype of the proposed high step-up converter is tested. The electrical specifications are V_{in} = 40 V, V_O = 550 V, and f_S = 40 kHz. The major components have been chosen as follows: Magnetizing inductors L_{m1} and L_{m2} = 133 μH; 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 μF; and C_1 = 470 μF. The design consideration of the proposed converter includes component selection and coupled inductor designs which are based on the analysis presented in the previous section. In the proposed converter, the values of the primary leakage inductors of the coupled inductors are 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 performances of high step-up gain, the turn ratio n can be set as one for the prototype circuit with 40-V input voltage and 550-V output to reduce cost, volume, and conduction loss of the winding. Thus, the copper resistances which affect efficiency much can be decreased.

4.1 Simulation Results

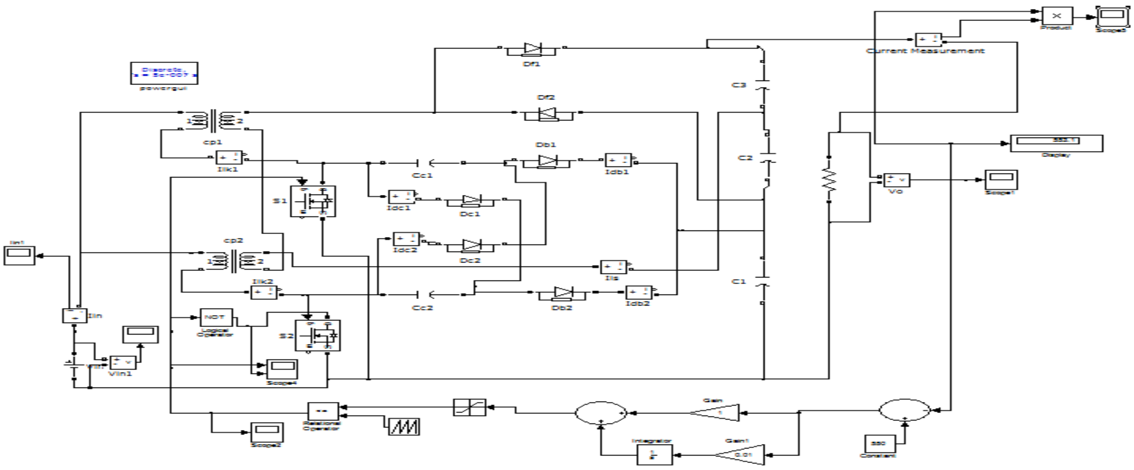


Fig. 6.Simulink model of closed loop control of interleaved converter with voltage multiplier module

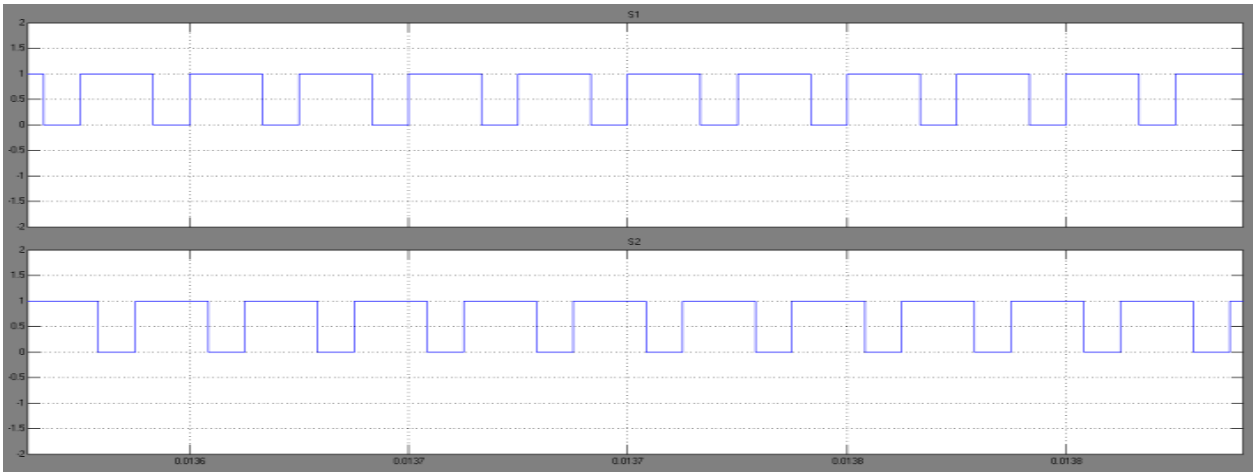


Fig.7.Gating pulse of power switches S1 and S2

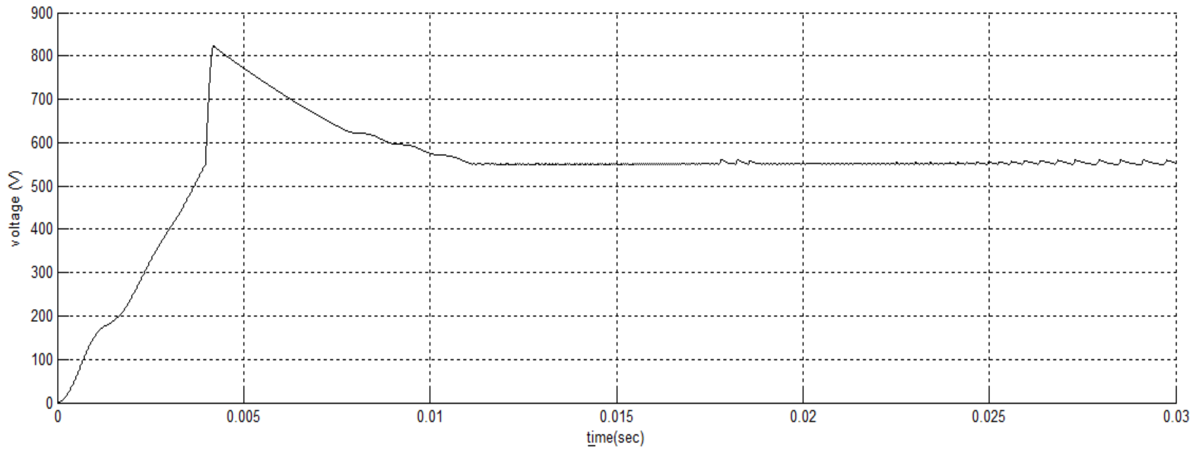


Fig.8.Output voltage of closed loop control of interleaved converter with voltage multiplier module

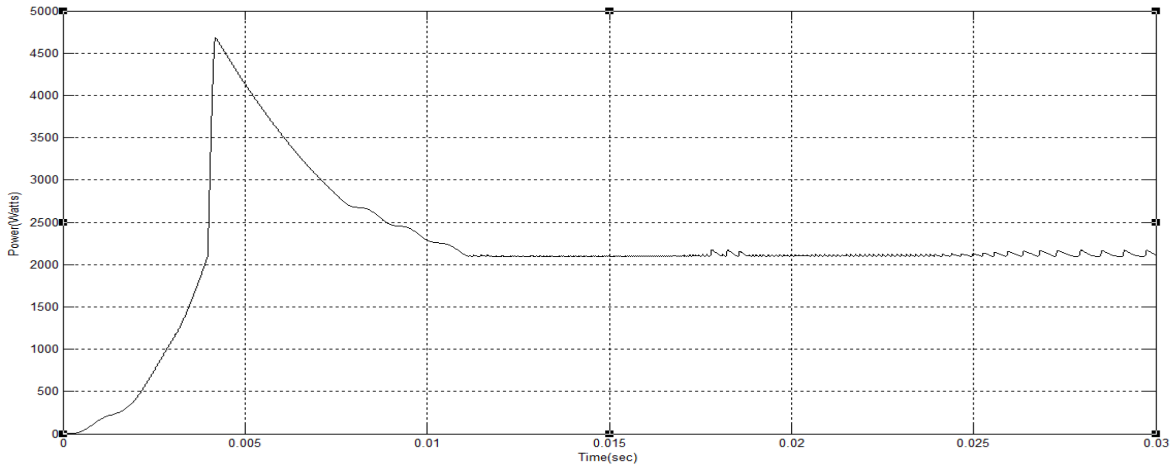


Fig.9. Measurement of power from the proposed circuit Simulink model

V. CONCLUSION

This paper has presented the theoretical analysis of steady state, related consideration, simulation results, and experimental results for the proposed converter. The proposed converter has successfully implemented an efficient high step-up con- version through the voltage multiplier module. The interleaved structure reduces the input current ripple and distributes the cur- rent 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 finally the proposed converter output voltage (550 V). Thus, the proposed converter is suitable for high-power or renewable energy applications that need high step-up conversion.

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