Novel Step-up DC-to-DC Converter with Isolated Transformer and Switched-Clamp Capacitor Techniques for Renewable Systems

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Abstract: A high step-up DC-to-DC converter that integrates an isolated transformer and a switched-clamp capacitor is presented in this study. The voltage stress of the main power switch should be clamped to 1/4 \( V \) by using the turn ratio and switched-clamp capacitor of an isolated transformer to achieve a high voltage gain. In addition, a passive clamp circuit is employed to reduce voltage stress on the main power switch. The energy of the leakage inductor can be recycled by the clamp capacitor because of the passive clamp circuit, thereby improving the power converter efficiency. The converter consists of one isolated transformer, one main switch, three capacitors, and four diodes. Operating principle and steady-state analyses are also discussed. Finally, a 24-V-input voltage to 200-V-output voltage and a 150 W output power prototype converter are fabricated in the laboratory. The maximum efficiency of the converter is 95.1% at 60 W.

Keywords: high voltage gain; switch-clamp capacitor; DC–DC converter; renewable energy

1. Introduction

In the 21st century, the rapid industrial development has caused severe environmental pollution. The extent of damage to the environment has become irreparable. To obtain power and energy, substantial natural resources have been depleting because of massive exploitation of oil and natural gases. In particular, severe air pollution has been caused by coal combustion. In view of this phenomenon, a number of recommendations had been proposed in the 2015 Paris United Nations Climate Change Conference (i.e., COP21 or CMP11) to cope with the changing climate, as follows: (1) The global average temperature should be controlled within 2 °C of the pre-industrial temperature, and (2) the universal availability of sustainable energy should be promoted in developing countries to strengthen the use of renewable energy sources [1]. Therefore, renewable energy technologies are being investigated, focusing on developing a new high step-up circuit architecture and using renewable energy as the main power source through direct current (DC) to alternating current (AC) inverter technology [2]–[4]. The current mainstream renewable energy sources are wind and solar energies. The proposed renewable energy output voltage has a low-voltage system that requires high step-up circuits to be converted to high output voltage systems [5]–[7]. A simple but highly efficient circuit structure should be designed to comply with the security rules of the isolation circuit architecture [8].

The National Synchrotron Radiation Research Center of Taiwan costs $100 million. The solar modules from TYNSSOLAR Co., Ltd. comprise a single photovoltaic module that can reach a maximum power of 150 W and a maximum input voltage of 24 V. In this study, a group of high step-up circuits were developed within the TYNSSOLAR photovoltaic module group of the converter.
Several basic circuits, such as the boost and flyback converters, can take high step-up voltage gains for extreme duty cycles. 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 inductor of the transformer will cause high power dissipation and high voltage spikes on the main power switch. Therefore, a main power switch with high stress voltage must be selected because of excessive cost and space issues.

Many topologies of high step-up converters have been proposed, including coupled inductor technology [9]–[12], switched-clamp capacitor technology [13]–[15], and isolated transformer technology [16]–[19]. Coupled inductor technology can cause substantial leakage inductance. A snubber circuit can absorb leaked energy; however, the circuit efficiency may be reduced. A switched-clamp capacitor can store energy when the switch is turned on. When the power is switched off after, the energy in the capacitor is delivered to the output loading. However, the electric system prevents current flow and no direct conduction path is permitted. As a result, the isolated transformer technology has been proposed to meet the safety standards of galvanic isolation [20]. This technique can easily achieve a high output voltage that uses turn ratio to achieve high voltage gain. The technology can be set to the required voltage by adjusting the turn ratio and duty cycle. An isolated step-up DC–DC converter is suitable as a renewable energy source in low-output-voltage systems. Moreover, this converter can produce high voltage output and achieve isolation. However, an isolated transformer can also produce leakage inductance; thus, a clamp circuit is necessary to recycle energy and achieve high efficiency [21]–[25].

In this study, a high step-up and high efficiency DC–DC converter is proposed. The input source is photovoltaic renewable energy, which is transferred to output loading through the proposed high step-up DC–DC converter circuit. The use of a clamp circuit can prevent spikes and clamping voltage stresses on the switch. When choosing switching elements, selecting low $R_{\text{ds(on)}}$ components can reduce conduction losses. An isolated transformer can be viewed as a forward converter that transfers energy to the secondary side when the switch is turned on. At the same time, the switched-clamp and clamp circuit capacitors also transfer energy to the loading. When the switch is turned off, the clamp circuit absorbs the energy stored in the leakage inductance, whereas the switched-clamp capacitor can store energy from the primary side. The proposed circuit architecture can achieve a step-up output voltage through duty cycle modulation. Moreover, the passive clamp circuit can obtain recycled energy, and the clamping voltage stress on the switch can facilitate a high efficiency power converter.

The features of the proposed converter are as follows:
(1) satisfies the safety standards for galvanic isolation;
(2) small isolated transformer;
(3) high step-up voltage gain;
(4) recycles leakage inductor energy and clamps voltage stress on the main switch through the passive clamp circuit;
(5) high efficiency.

2. Operation Principle of the Proposed Converter

For the proposed converter, an integrated switched-clamp capacitor and isolated transformer can achieve high voltage gain and clamp spike voltage on the main power switch. However, the proposed converter needs a highly effective capacitor $C_1$ and diodes $D_1$ and $D_2$. This section details the operating modes at continuous conduction mode (CCM) and discontinuous conduction mode (DCM) during a switching period.

Fig. 1 illustrates the proposed converter structure. The proposed converter circuit consists of isolated transformers $N_p$ and $N_s$, the main power switch $S$, and a secondary side step-up circuit that has diodes $D_4$ and $D_5$ and capacitor $C_2$. The clamp circuit has diodes $D_1$ and $D_2$, capacitor $C_1$, and large output capacitors $C_{o1}$ and $C_{o2}$. The leakage inductor energy loss is recycled by a passive clamp circuit capacitor $C_i$ that clamps the voltage stress on the main switch.
Before discussing the circuit operation principles, the following conditions were assumed to simplify the analysis of the proposed converter:

1. Capacitors $C_1$, $C_2$, $C_{o1}$, and $C_{o2}$ are sufficiently large. Thus, $V_{C1}$, $V_{C2}$, $V_{Co1}$, and $V_{Co2}$ are constant during operation.

2. The parasitic capacitor of power devices is not neglected.

3. The coupling coefficient is defined as $k$, which is equal to $L_m/(L_m + L_s)$. The magnetizing inductance is $L_m$ and the leakage inductance is $L_s$.

4. Turn ratio $n$ is equal to $N_s/N_p$.

![Fig. 1. Circuit configuration of the proposed converter](image)

The CCM and DCM of the proposed converter operation are analyzed in detail.

### 2.1 CCM operation analysis

The key component of the current and voltage waveforms of the proposed converter at CCM is presented in Fig. 2. In CCM, the proposed converter has five operating modes that are classified based on the switch duty cycle.

**Mode I [$t_0$, $t_1$]:** During this period, power switch $S$ is turned on. The equivalent circuit is illustrated in Fig. 3a. The clamp circuit diode $D_1$ and step-up circuit diode $D_3$ are forward-biased. The DC source supplies energy to the leakage magnet and transfers energy to the secondary side capacitor $C_2$ through the step-up circuit-isolated transformer. When diode $D_3$ is turned on, clamp circuit capacitor $C_1$ releases energy to the high voltage output capacitor $C_{o2}$. Therefore, the leakage magnet $i_{Lk}$ and clamp circuit current $i_{d2}$ increase linearly, whereas the secondary side leakage inductor current $i_d$ decreases to zero. $V_{C2}$ is approximately $nV_{L1}$, $V_{C1}$ is equal to $V_{Co2}$, and the voltage of parasitic capacitor on the main power switch is zero. This operating mode ends when the current of secondary side $i_d$ is zero at $t = t_1$.

**Mode II [$t_1$, $t_2$]:** During this period, power switch $S$ remains turned on. The equivalent circuit is indicated in Fig. 3b. The clamp circuit diode $D_1$ and step-up circuit diode $D_4$ are forward-biased. The DC source supplies energy to the leakage magnet $L_{kp}$ and magnetizes inductor $L_m$. The secondary side capacitor $C_2$ and isolated transformer secondary coil discharge energy to the high voltage...
output capacitor \( C_{\text{oi}} \), and the clamp circuit capacitor \( C_1 \) releases energy to the high voltage output capacitor \( C_{\text{o2}} \). Thus, the leakage magnet \( i_{Lk} \) and magnetizing inductor current \( i_{Lm} \) increase linearly; and \( V_{c2} \) is approximately equal to \( V_{c1} - nV_{L1} \), and \( V_{c1} \) is equal to \( V_{co} \), and voltage of parasitic capacitor on main power switch is zero. In this mode, the input source, magnetizing inductance, as well as the capacitor \( C_1 \) and capacitor \( C_2 \) energy, will be transmitted to the output capacitors \( C_{\text{oi}} \) and \( C_{\text{o2}} \). This operating mode ends when the power switch is turned off at \( t = t_2 \).

Mode III \([t_2, t_3]\): During this period, power switch \( S \) is turned off. The equivalent circuit is displayed in Fig. 4a. Clamp circuit diode \( D_1 \) and step-up circuit diode \( D_4 \) are forward-biased. The DC source and leakage magnet \( L_{kp} \) supply energy to the magnetizing inductor \( L_m \) and parasitic capacitor \( C_{\text{oa}} \) of the main power switch \( S \). Secondary side capacitor \( C_2 \) and secondary coil current \( i_s \) increase linearly; output capacitors \( C_{\text{oi}} \) and \( C_{\text{o2}} \) provide energy to output loading, and voltage of parasitic capacitor on main power switch is equal to \( V_{\text{in}} - V_{L1} \). This mode ends when the parasitic capacitor \( C_{\text{oa}} \) energy becomes fully charged.

Mode IV \([t_3, t_4]\): During this period, power switch \( S \) is turned off at \( t = t_3 \). The equivalent circuit is illustrated in Fig. 4b. Diodes \( D_1 \) and \( D_4 \) are forward-biased. Magnetizing inductor \( L_m \) and passive clamp circuit capacitor \( C_1 \) charge energy via leakage inductor \( L_a \). Leakage inductor current \( i_{Lk} \) decreases quickly because the energy is recycled by capacitor \( C_1 \). Secondary coil energy and capacitor \( C_2 \) continuously discharge energy to the high voltage side capacitor \( C_{\text{oa}} \), and voltage of parasitic capacitor on main power switch is equal to \( V_{\text{oa}} \). This mode ends at \( t = t_4 \) until capacitor \( C_2 \) voltage is equal to the output capacitor \( C_{\text{oa}} \) voltage.

Mode V \([t_4, t_5]\): During this period, power switch \( S \) is turned off. The equivalent circuit is illustrated in Fig. 4c. \( D_1 \) and \( D_3 \) are forward biased. DC source \( V_{\text{in}} \) and magnetizing inductor \( L_m \) discharge energy to capacitor \( C_1 \), whereas capacitor \( C_2 \) charges energy via \( D_3 \) by secondary coil induced energy; voltage of parasitic capacitor on main power switch is equal to \( V_{\text{oa}} \). Power switch \( S \) is turned on at the next period at \( t = t_5 \), during which this mode ends.
Fig. 2. Current and voltage waveforms of the key components of the proposed converter at CCM
Fig. 3. Operating modes at CCM (switch turned on) during a switching period

(a) Mode I

(b) Mode II
2.2 DCM operation analysis

In this section, the proposed circuit operation at DCM will be discussed. The leakage inductor $L_k$ and parasitic capacitor of main power switch will not be discussed to simplify the analysis. The key component current and voltage waveforms are presented in Fig. 5. Fig. 6 presents the proposed circuit in modes I to III during operation.

Mode I [$t_0$, $t_1$]: Power switch $S$ is turned on. The proposed converter equivalent circuit is shown in Fig. 6a. $D_2$ and $D_4$ are forward-biased. DC source $V_{in}$ supplies energy to magnetizing inductor $L_m$, and the magnetizing inductor current $i_{m}$ increases linearly. Secondary side capacitor $C_2$ and secondary coil discharge energy to capacitor $C_1$. Passive clamp circuit capacitor $C_1$ then discharges energy to capacitor $C_{o1}$. Serial output capacitors $C_{o1}$ and $C_{o2}$ provide energy to output loading. This mode ends when power switch $S$ is turned off at $t = t_1$. 

Mode II [$t_1$, $t_2$]: Power switch $S$ is turned off at this period. The proposed converter equivalent circuit is exhibited in Fig. 6b. $D_1$ and $D_3$ are forward-biased. DC source $V_{in}$ and magnetizing inductor $L_m$ supply energy to secondary side coil and capacitor $C_1$. The $C_2$ capacitor via $D_3$ charges energy via the secondary coil of the isolated transformer. This mode ends when the magnetizing inductor current $i_{m}$ is equal to zero at $t = t_2$.

Mode III [$t_2$, $t_3$]: Power switch $S$ is turned off at this period. The proposed converter equivalent circuit is illustrated in Fig. 6c. All the diodes are turned off and high voltage side-output capacitors $C_{o1}$ and $C_{o2}$ provide energy to output loading. This mode ends at $t = t_3$, and power switch $S$ is turned on at the next period.
Fig. 5. Current and voltage waveforms of the key components of the proposed converter at DCM operation.
Fig. 6. Operating modes at DCM during a switching period

a Mode I
b Mode II
c Mode III

3. Steady-state Analysis

The steady-state analysis of the proposed converter is discussed in this section. The assumed condition equations of turn ratio and coupling coefficients $k$ are defined as follows:

$$n = \frac{N_s}{N_p} \quad (1)$$

$$k = \frac{k_{lm}}{L_m + L_k} \quad (2)$$

To simplify the steady-state analysis, any $L_k$ value smaller than $L_m$ is neglected, and coupling coefficient $k$ should be equal to 1. Modes I, III, and IV are short and disregarded by one switching cycle. The time intervals of modes II and V are considered.

3.1 CCM operation analysis

$V_{L1}$ and $V_{L2}$ are across voltages at mode II. The following equations can be derived from Fig. 3b:

$$V_{L1}^{II} = V_{in} \quad (3)$$

$$V_{L2}^{II} = nV_{L1}^{II} = nV_{in} \quad (4)$$

Based on mode V, capacitor $C_1$ charges the DC source, and the primary coil and capacitor $C_2$ charge the secondary coil. The across voltages of $V_{L1}^{II}$ and $V_{L2}^{II}$ can be written as:

$$V_{L1}^{V} = V_{in} - V_{c1} \quad (5)$$

$$V_{L2}^{V} = -V_{c2} \quad (6)$$

According the volt-second balance principle, the voltage equations of $N_p$ and $N_s$ are expressed as:

$$\int_0^{DT} V_{L1}^{II} dt + \int_{DT}^{T} V_{L1}^{V} dt = 0 \quad (7)$$

$$\int_0^{DT} V_{L2}^{II} dt + \int_{DT}^{T} V_{L2}^{V} dt = 0 \quad (8)$$

By using (3) and (5) into (7), the stress voltage of $N_p$ in a switching period can be obtained by:

$$V_{in}(DT) + (V_{in} - V_{c1})(1 - DT) = 0 \quad (9)$$

$$V_{c1} = V_{in}/(1 - D) \quad (10)$$
According to (4) and (6) to (8), stress voltage of \( N_s \) in a switching period can be arranged as:

\[
V_{n_s}^i = nV_{in}(DT_s) + (-V_{c2})(1 - DT_s) = 0
\]  

(11)

\[
V_{c2} = nDV_{in}/(1 - D)
\]  

(12)

At mode II, capacitor \( C_1 \) releases energy to capacitor \( C_{o1} \) and capacitor \( C_2 \) and the secondary coil release energy to capacitor \( C_{o1} \). The across voltages of \( V_{c01}, V_{c02}, \) and \( V_o \) are derived by:

\[
V_{c01} = V_{c2} + V_{L2}^i
\]  

(13)

\[
V_{c02} = V_{c1}
\]  

(14)

\[
V_o = V_{c1} + V_{c2} + V_{L2}^i
\]  

(15)

By substituting (12) and (4) into (13), and (10) into (14), the stress voltage of capacitors \( C_{o1} \) and \( C_{o2} \) can be rewritten as:

\[
V_{c01} = nDV_{in}/(1 - D) + nV_{in}
\]  

(16)

\[
V_{c02} = V_{in}/(1 - D)
\]  

(17)

Substituting (4), (10), and (12) to (15), the output voltage equations can be expressed as:

\[
V_o = V_{in}/(1 - D) + nDV_{in}/(1 - D) + nV_{in}
\]

(18)

The voltage gain can obtained as follows:

\[
M_{CCM} = 0
\]  

(19)

The use of voltage-clamped technology to reduce reverse-recovery current and switch-voltage stress are discussed in the literature [24]. Circuit topology is the combination of an inductor and a transformer to increase the corresponding voltage gain. One additional inductor is a reduced reverse-current and one additional capacitor is a clamp voltage of the main power switch that can reduce switch-voltage stress. According to literature [24], voltage gain is \( M_{CCM[24]} = \frac{1+n}{1-D} \). Comparisons of the voltage gains of the proposed converter and one presented in a previous study [24] are shown in Fig. 7. The voltage gain of the proposed converter is higher than that of the converter presented in [24] (see Fig. 7).

\[
\frac{V_o}{V_{in}}
\]

<table>
<thead>
<tr>
<th>Proposed Converter</th>
<th>Converter in [24]</th>
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Fig. 7. Duty ratio versus voltage gain of the proposed converter compared with the converter in [24]; condition is CCM operation under \( k = 1 \) and \( n = 3 \).
3.2 DCM operation analysis

Three modes have been discussed at DCM operation. Fig. 5 illustrates the key component current and voltage waveforms.

Mode I: During this period, the main power switch $S$ is turned on and the magnetizing inductor charges the DC source. Fig. 6a presents the operation. The equation can be expressed as follows:

\begin{align*}
V_{L1}^{I} &= V_{in} \\
V_{L2}^{I} &= nV_{in}
\end{align*}

(20)

(21)

The peak current of the magnetizing inductor can be defined as:

\begin{equation}
I_{\text{Lmp}} = \frac{V_{\text{in}}}{L_{m}} DT_{s}
\end{equation}

(22)

The across voltages of $C_1$ and $C_2$ are given as:

\begin{align*}
V_{c2} &= V_{c01} - V_{L2}^{I} \\
V_{c1} &= V_{c02} \\
V_o &= V_{c1} + V_{c2} + V_{L1}^{I}
\end{align*}

(23)

(24)

(25)

Mode II: During this period, main power switch $S$ is turned off, and the input voltage and magnetizing inductor energy discharge energy to capacitor $C_1$. Fig. 6b illustrates the operating mode.

\begin{align*}
V_{L1}^{II} &= V_{in} - V_{c1} \\
V_{L2}^{II} &= -V_{c2}
\end{align*}

(26)

(27)

Fig. 6c presents mode III. The output capacitors $C_0$ and $C_2$ discharge energy to output loading.

\begin{align*}
V_{L1}^{III} &= V_{L2}^{III} = 0
\end{align*}

(28)

Based on the volt-second balance principle, the steady state operation of an inductor in a DC-DC converter and net inductor voltage in a switching period must be zero.

\begin{align*}
\int_0^{DT_{s}} V_{L1}^{I} \, dt + \int_0^{DT_{s}} V_{L2}^{I} \, dt + \int_0^{DT_{s}} V_{L1}^{II} \, dt = 0 \\
\int_0^{DT_{s}} V_{L2}^{I} \, dt + \int_0^{DT_{s}} V_{L2}^{II} \, dt + \int_0^{DT_{s}} V_{L2}^{III} \, dt = 0
\end{align*}

(29)

(30)

From (20), (26), and (28) to (29); and (21), (27), and (28) to (30), the stress voltages of capacitors $C_1$ and $C_2$ are:

\begin{align*}
V_{c1} &= \frac{V_{in} + D_{L}}{D_{L}} V_{in} \\
V_{c2} &= \frac{V_{in}}{D_{L}} V_{in}
\end{align*}

(31)

(32)

Substituting (21), (31), and (32) to (25), the voltage gain of the proposed converter at DCM can be obtained using:

\begin{align*}
V_o &= \left[ (1 + n) \left( 1 + \frac{D_{L}}{D_{L}} \right) \right] V_{in} \\
D_{L} &= \frac{(1+n)D_{V_{in}}}{V_{o} - (1+n)V_{in}}
\end{align*}

(33)

(34)

Based on Fig. 5, $i_{co}$ is the average current value of the output capacitor $C_0$, and the average values of the $I_{c1}$ and $I_{c0}$ can be calculated by:

\begin{align*}
I_{c0} &= I_{D4} - I_o \\
I_{c01} &= \frac{1}{2} \frac{D_{L}}{D_{L} + n} - I_o
\end{align*}

(35)

(36)

In the steady state, $I_{c01}$ equals zero. (22), (34), and $I_{c01} = 0$ can be substituted to (36). Thus, (36) can be rewritten as:

\begin{equation}
\frac{1}{2(n+1)} \cdot \left( \frac{V_{o}}{V_{in}} - (1+n)V_{in} \right) = V_{o} \frac{R}{R}
\end{equation}

(37)

The time constant of magnetizing inductance is defined as:

\begin{equation}
\tau_{Lm} = \frac{L_{m}}{R_{m}}
\end{equation}

(38)

Substituting (38) with (37), the voltage gain can be obtained by:

\begin{equation}
M_{\text{DCM}} = \frac{V_o}{V_{in}} = 1 + \frac{(1+n)^2}{2} + \frac{D_{L}}{2\tau_{Lm}}
\end{equation}

(39)

3.3 Boundary operating condition between CCM and DCM

The voltage gain is equal at CCM and DCM when the proposed converter operation is in boundary condition mode. Based on the formulas (19) and (39), the time constant $\tau_{LmB}$ of the boundary-normalized magnetizing inductor can be written as:

\begin{equation}
\tau_{LmB} = \frac{D_{L}^2 (1-D_{L})^2}{2(1+n+nD)^2 - (1+2n+n^2)(1-2D+D^2)}
\end{equation}

(40)
Fig. 8 indicates that, if the curve of $\tau$ is lower than that of $\tau_{Lmb}$, then the proposed converter operation is in DCM. Otherwise, if the curve of $\tau$ is higher than that of $\tau_{Lmb}$, then the proposed converter operation is in CCM.

![Graph of Duty ratio versus $\tau_{Lmb}$](image)

**Fig. 8.** Duty ratio versus $\tau_{Lmb}$ at the boundary condition of the proposed converter under $n = 3$

### 4. Experimental Results of the Proposed Converter

A 150 W isolated converter was built in the laboratory to prove its effectiveness and performance. The input DC voltage was 24 V, and the output voltage was 200 V. The main power switch $S$ selected had low conduction, low voltage stress components, and with a switch frequency of 50 kHz. The main specifications are presented in Table 1.

The experimental results can be divided into current and voltage waveform testing results. Fig. 9 illustrates the proposed converter current waveform of the key components at full load. The input voltage was 24 V, and the output power was 150 W. Fig. 9a presents the isolated transformer primary and secondary currents along with the drain to source voltage from the main power switch. Drain to source voltage of the main power switch was 0 V when the main switch was turned on, and when the primary current linearly increased, the peak current of the magnetizing inductor is $I_{Lmp} = \frac{V_{in}}{L_m} DT_s$. Otherwise, voltage of the main power switch was $V_{ds} = V_{in} + V_{L1}$ and current of the magnetizing inductor is $I_{Lmp} = \frac{V_{in} - V_{C1}}{L_m} DT_s$ until it decreased the current to zero when the main power switch was turned off. Fig. 9b presents the diode current versus $V_{ds}$. The waveforms of $i_{in}$ and $i_C$ illustrate that capacitor $C_1$ charges and discharges when the main switch is turned on and off, respectively. Capacitor $C_1$ releases energy through $D_3$ and the main power switch to output capacitor $C_o1$, and $i_C$ is the forward current when the main power switch is turned on. At the next period, capacitor $C_1$ was charged by magnetizing the inductor and input source. Moreover, the voltage of main power switch was clamped to $V_{C1}$ through diode $D_1$. $i_C$ is the forward current when the main power switch is turned off. Fig. 9c illustrates that the waveforms of $i_o$ and $i_C$ reveals that capacitor $C_2$ charges energy to the secondary coil through $D_5$ and $i_o$ is the forward current when the main power switch is turned on. Otherwise, capacitor $C_2$ discharges energy to capacitor $C_o2$ through $D_4$ and $i_o$ is the forward current when the main switch is turned off. Figs. 10a and 10b exhibit the measurements of the waveform of the capacitor voltages. Fig. 10a presents the measurements of the capacitor voltages of $C_1$ and $C_2$ that can satisfy formulas (10) and (12). Capacitor $C_1$ releases energy through $D_5$ and is charged via the input source and magnetizing inductor. Capacitor $C_2$ changed to secondary coil via diode $D_3$ and discharged energy to secondary coil and output capacitor $C_o2$.
through diode $D_4$. Fig. 10b displays the measurements of the capacitor voltages of $C_{\alpha}$ and $C_{\beta}$. $V_{c_{\alpha}1}$, $V_{c_{\beta}2}$, and $V_o$ test results are satisfied by (16), (17), and (18). Voltage of capacitor $C_{\beta}$ is equal to voltage of capacitor $C_{\alpha}$. Voltage of capacitor $C_{\alpha}$ is equal to $V_{c_{\beta}2} + V_{o1}^{h}$. Output voltage is sum to $V_{c_{\alpha}1}$ and $V_{c_{\beta}2}$. Finally, the measured efficiency of the proposed converter is within 30–150 W (see Fig. 11), and the maximum efficiency is 95.1% at 60 W.

<table>
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<th>Table 1. Specifications of the proposed converter</th>
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<td>Parameter</td>
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<td>Input voltage</td>
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<td>Output voltage</td>
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<td>Maximum output power</td>
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<td>Main switch frequency</td>
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<td>Main switch</td>
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<td>Diodes</td>
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<td>Capacitors</td>
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<td>Capacitor</td>
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<tr>
<td>Turn ratio</td>
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<td>Isolated transformer</td>
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<td>Coupling coefficient</td>
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Fig. 9. Experimental current waveform under full-load $P_o = 150$ W

(a) Measured waveforms of $v_o$, $i_o$, and $i_v$

(b) Measured waveforms of $v_o$, $i_o$, and $i_o$

(c) Measured waveforms of $v_o$, $i_o$, and $i_o$
Fig. 10. Experimental voltage waveform under full-load $P_o = 150$ W

(a) Measured waveforms of $v_1$, $v_2$, and $v_3$

(b) Measured waveforms of $v_{co1}$, $v_{co2}$, and $v_o$

5. Conclusions

In this study, a high step-up voltage circuit was successfully designed and fabricated in the laboratory. The proposed converter uses an isolated transformer and a clamp capacitor circuit to achieve high voltage gain. The clamp capacitor circuit can be used to recycle the energy of the
primary leakage inductor and reduce the voltage spike of the main power switch when the power switch is turned off. Thus, low voltage stress and conducting resistance $R_{ds(on)}$ component can be selected to ensure reduced switch loss on the power switch, thereby improving the efficiency of the proposed converter. Finally, a full power of a 150 W high step-up converter with an input voltage of 24 V and output voltage of 200 V was achieved. The experimental results demonstrated high efficiency of the proposed converter, with peak efficiency of 95.1%. In addition, the voltage stress on the main power switch is clamped at 50 V.

**Supplementary**

**Conflicts of Interest:** State any potential conflicts of interest here or “The authors declare no conflict of interest”.

**References**

1. UNFCCC., ‘Paris Agreement’ (Publisher, 2015), pp. 1-2


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