A coupled inductor integrated with boost converter is used in the system. There are two results from low input voltage; therefore, low efficiency and the parasitic resistances of switches or the reverse recovery of diode voltage multiplier yield becomes significantly reduced [2]. An ac module is a microinverter configured on the rear bezel of a PV panel [1], [3]; this alternative solution not only immunizes against the yield loss by shadow effect, but also provides flexible installation options in accordance with the user’s budget [4]. Many prior research works have proposed a single-stage dc–ac inverter with fewer components to fit the dimensions of the bezel of the ac module, but their efficiency levels are lower than those of conventional PV inverters.

The power capacity range of a single PV panel is about 100 W to 300 W, and the maximum power point (MPP) voltage range is from 15 V to 40 V, which will be the input voltage of the ac module; in cases with lower input voltage, it is difficult for the ac module to reach high efficiency [3]. However, employing a high step-up dc–dc converter in the front of the inverter improves power-conversion efficiency and provides a stable dc link to the inverter. When installing the PV generation system during daylight, for safety reasons, the ac module outputs zero voltage [4], [5]. There are two major concerns related to the efficiency of a high step-up dc–dc converter: large input current and high output voltage. The large input current results from low input voltage; therefore, low-voltage-rated devices with low $R_{DS\,on}$ are necessary in order to reduce the conduction loss.

Previous research on various converters for high step-up applications has included analyses of the switched-inductor and switched-capacitor types [6], [7]; transformer less switched-capacitor type [8], [9], [29]; the voltage-lift type [12]; the capacitor-diode voltage multiplier [13]; and the boost type integrated with a coupled inductor [10], [11], these converters by increasing turns ratio of coupled inductor obtain higher voltage gain than conventional boost converter. Some converters successfully combined boost and flyback converters, since various converter combinations are developed to carry out high step-up voltage gain by using the coupled-inductor technique [14]–[19], [27], [28]. The efficiency and voltage gain of the dc–dc boost converter are constrained by either the parasitic effect of the power switches or the reverse recovery issue of the diodes. In addition, the equivalent series resistance (ESR) of the capacitor and the parasitic resistances of the inductor also affect overall efficiency. Use of active clamp technique not only recycles the leakage inductor’s energy but also constrains the voltage stress across the active switch, however the trade

A High Step-Up DC–DC Converter for Photovoltaic Applications

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ABSTRACT: Photovoltaic (PV) power-generation systems are becoming increasingly important and prevalent in distribution generation systems. The dc–dc converter requires large step-up conversion from the panel’s low voltage to the voltage level of the application. A coupled inductor integrated with boost converter is used in the system. The proposed converter has several features: The connection of the two pairs of inductors, capacitor, and diode gives a large step-up voltage-conversion ratio; the leakage-inductor energy of the coupled inductor can be recycled, thus increasing the efficiency and restraining the voltage stress across the active switch; and the floating active switch efficiently isolates the PV panel energy during non-operating conditions, which enhances safety. In this paper detailed operating principles and steady-state analyses of continuous modes are described. A 15 V input voltage, 200 V output voltage, and 200 W output power prototype circuit of the proposed converter has been simulated.

KEYWORDS: PV cells, Boost converter, coupled inductor, high step-up voltage gain, and single switch.

1. INTRODUCTION

IN RECENT years, growing concerns for the environment have led to increased interest in natural energy sources. A centralized PV array is a serial connection of numerous panels to obtain higher dc-link voltage for main electricity through a dc–ac inverter [1], [30]. Unfortunately, once there is a partial shadow on some panels, the system’s energy yield becomes significantly reduced [2]. An ac module is a microinverter configured on the rear bezel of a PV panel [1]–[3]; this alternative solution not only immunizes against the yield loss by shadow effect, but also provides flexible installation options in accordance with the user’s budget [4]. Many prior research works have proposed a single-stage dc–ac inverter with fewer components to fit the dimensions of the bezel of the ac module, but their efficiency levels are lower than those of conventional PV inverters.
off is higher cost and complex control circuit [25], [26]. By combining active snubber, auxiliary resonant circuit, synchronous rectifiers, or switched-capacitor-based resonant circuits and so on, these techniques made active switch into zero voltage switching (ZVS) or zero current switching (ZCS) operation and improved converter efficiency [20]– [24]. However when the leakage-inductor energy from the coupled inductor can be recycled, the voltage stress on the active switch is reduced, which means the coupled inductor employed in combination with the voltage-multiplier or voltage-lift technique successfully accomplishes the goal of higher voltage gain [6]– [13]. The Fig. 1 shows the basic block diagram of proposed system.

The proposed converter, shown in Fig. 2, is comprised of a coupled inductor T1 with the floating active switch S1. The primary winding N1 of a coupled inductor T1 is similar to the input inductor of the boost converter, and capacitor C1 and diode D1 receive leakage inductor energy from N1. The secondary winding N2 of coupled inductor T1 is connected with another pair of capacitors C2 and diode D2, which are in series with N1 in order to further enlarge the boost voltage. The rectifier diode D3 connects to its output capacitor C3.

During boost operation, when switches S1 is turned ON, the primary and secondary windings of the coupled inductor are operated in series-discharge to achieve high step-up voltage gain. The operating principles and steady-state analysis of the proposed converter are presented in the following sections [21–24].

### II. OPERATING PRINCIPLES OF THE PROPOSED CONVERTER

The simplified circuit model of the proposed converter is shown in Fig. 3. The coupled inductor T1 is represented as a magnetizing inductor $L_m$, primary and secondary leakage inductors $L_k1$ and $L_k2$, and an ideal transformer. In order to simplify the circuit analysis of the proposed converter, the following assumptions are made [26–27].

1) All components are ideal, except for the leakage inductance of coupled inductor $T_1$, which is being taken under consideration. The on-state resistance $R_{DS(ON)}$ and all parasitic capacitances of the main switch $S_1$ are neglected, as are the forward voltage drops of diodes $D_1$–$D_3$. [28–30]
2) The capacitors $C_1 \sim C_3$ are sufficiently large that the voltages across them are considered to be constant.[14-17]
3) The ESR of capacitors $C_1 \sim C_3$ and the parasitic resistance of coupled inductor $T_1$ are neglected.
4) The turns ratio $n$ of the coupled inductor $T_1$ windings is equal to $N_2 / N_1$.

The operating principle of continuous conduction mode (CCM) is presented in detail. The current waveforms of major components are given in Fig. 5. There are five operating modes in a switching period. The operating modes are described as follows.[18-20]

**Continuous conduction mode (CCM) operation**

**Mode 1 $[t_0, t_1]$**
In this transition interval, the magnetizing inductor $L_m$ continuously charges capacitor $C_2$ through $T_1$ when $S_1$ is turned ON. The current flow path is shown in Fig. 4(a) switch $S_1$ and diode $D_2$ is conducting. The current $i_{Lm}$ is decreasing because source voltage $V_{in}$ crosses magnetizing inductor $L_m$ and primary leakage inductor $L_{k1}$ magnetizing inductor $L_m$ is still transferring its energy through coupled inductor $T_1$ to charge switched capacitor $C_2$, but the energy is decreasing the charging current $i_{D2}$ and $i_{C2}$ are decreasing. The secondary leakage inductor current $i_{Lk2}$ is declining as equal to $i_{Lm} / n$. Once the increasing $i_{Lk1}$ equals decreasing $i_{Lm}$ at $t = t_1$, this mode ends.[24-25]

**Mode 2 $[t_1, t_2]$**
During this interval, source energy $V_{in}$ is series connected with $N_2$, $C_1$, and $C_2$ to charge output capacitor $C_3$ and load $R$; meanwhile magnetizing inductor $L_m$ is also receiving energy from $V_{in}$. The current flow path is shown in Fig.4(b), where switch $S_1$ remains ON and only diode $D_3$ is conducting. The $i_{Lm}$, $i_{Lk1}$, and $i_{D3}$ are increasing because the $V_{in}$ is crossing $L_{k1}$, $L_m$, and primary winding $N_1$; $L_m$ and $L_{k1}$ are storing energy.

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**Fig 4 Current flow path of five operating modes during one switching period at CCM operation. (a) Mode I: $t_0 \sim t_1$. (b) Mode II: $t_1 \sim t_2$ (c) Mode III: $t_2 \sim t_3$ (d) Mode IV: $t_3 \sim t_4$. (e) Mode V: $t_4 \sim t_5$.**
from $V_{in}$ meanwhile $Vin$ is also serially connected with secondary winding $N_2$ of coupled inductor $T_1$, capacitors $C_1$, and $C_2$, and then discharges their energy to capacitor $C_3$ and load $R$. The $i_{m}$, $i_{D1}$ and discharging current $|i_{C1}|$ and $|i_{C2}|$ are increasing. This mode ends when switch $S_1$ is turned OFF at $t = t_2$.

Mode 3 [$t_2$, $t_3$]
During this transition interval, secondary leakage inductor $L_{k2}$ keeps charging $C_3$ when switch $S_1$ is OFF. The current flow path is shown in Fig.4(c), where only diode $D_1$ and $D_3$ are conducting. The energy stored in leakage inductor $L_{k3}$ flows through diode $D_1$ to charge capacitor $C_1$ instantly when $S_1$ is OFF. Meanwhile, the energy of secondary leakage inductor $L_{k2}$ is series connected with $C_2$ to charge output capacitor $C_3$ and the load. Because leakage inductance $L_{k1}$ and $L_{k2}$ are far smaller than $L_m$, $i_{Lk2}$ rapidly decreases, but $i_{Lm}$ is increasing because magnetizing inductor $L_m$ is receiving energy from $L_{k1}$. Current $i_{Lk2}$ decreases until it reaches zero; this mode ends at $t = t_3$. 

Mode 4 [$t_3$, $t_4$]
During this transition interval, the energy stored in magnetizing inductor $L_m$ is released to $C_1$ and $C_2$ simultaneously.[31-33] The current flow path is shown in Fig.4(d). Only diodes $D_1$ and $D_2$ are conducting. Currents $i_{Lk1}$ and $i_{Lm}$ are continually decreased because the leakage energy still flowing through diode $D_1$ keeps charging capacitor $C_1$. The $L_m$ is delivering its energy through $T_1$ and $D_2$ to charge capacitor $C_2$. The energy stored in capacitor $C_3$ is constantly discharged to the load $R$. These energy transfers result in decreases in $i_{Lk1}$ and $i_{Lm}$ but increases in $i_{Lk2}$. This mode ends when current $i_{Lk1}$ is zero, at $t = t_4$.

Mode 5 [$t_4$, $t_5$]
During this interval, only magnetizing inductor $L_m$ is constantly releasing its energy to $C_2$. The current flow path is shown in Fig.4(d), in which only diode $D_2$ is conducting. The $i_{Lm}$ is decreasing due to the magnetizing inductor energy flowing through the coupled inductor $T_1$ to secondary winding $N_2$, and $D_2$ continues to charge capacitor $C_2$. The energy stored in capacitor $C_3$ is constantly discharged to the load $R$.[34] This mode ends when switch $S_1$ is turned ON at the beginning of the next switching period.
III. STEADY-STATE ANALYSIS OF PROPOSED CONVERTERS

To simplify the steady-state analysis, only modes 2 and 4 are considered for CCM operation, and the leakage inductances on the secondary and primary sides are neglected. The following equations can be written from Fig. 4:

\[ V_{Lm} = V_{in} \]
\[ V_{N2} = nV_{in} \]

During mode 4:
\[ V_{Lm} = -V_{C1} \]
\[ V_{N2} = -V_{C2} \]

Applying a volt-second balance on the magnetizing inductor \( L_m \) yields,
\[ \int_{0}^{T_S} V_{IN} \, dt + \int_{0}^{T_S} nV_{in} \, dt = 0 \]
\[ \int_{0}^{T_S} V_{C1} \, dt = 0 \]
\[ \int_{0}^{T_S} V_{12} \, dt = 0 \]

From which the voltage across capacitors \( C_1 \) and \( C_2 \) are obtained as follows:

\[ V_{C1} = \frac{D}{1-D} V_{IN} \]
\[ V_{C2} = \frac{nD}{1-D} V_{IN} \]

During mode 2 the output voltage \( V_O = V_{in} + V_{N2} + V_{C2} + V_{C1} \) becomes:
\[ V_O = \frac{nD}{1-D} V_{IN} + \frac{D}{1-D} V_{IN} \]

The DC voltage gain \( M_{CCM} \) can be found as follows:
\[ M_{CCM} = \frac{V_{OUT}}{V_{IN}} \]

The voltage stresses on \( S_1 \) and \( D_1 \rightarrow D_3 \) are given as:
\[ V_{DS} = V_{Di} = \frac{V_{IN}}{1-D} \]
\[ V_{D2} = \frac{nV_{IN}}{1-D} \]
\[ V_{D3} = \frac{(1+n)V_{IN}}{1-D} \]

IV. EXPERIMENTAL RESULTS

A 100 W prototype sample is presented to verify the practicability of the proposed converter. The electrical specifications are \( V_{in} = 15 \text{ V} \), \( V_O = 200 \text{ V} \), \( f = 50 \text{ kHz} \), and full-load resistance \( R = 400 \text{ O} \). The major components required are \( C_S = 47 \text{ µF} \) and \( C_3 = 220 \text{ µF} \). Since assign turns ratio \( n = 5 \), the duty ratio \( D \) is derived as 55%. The following figures shows the PV output voltage, power output from converter, voltage and current waveforms, which are measured from active switch S and the current waveforms of \( C_1, C_2 \) and \( L_m \).
Fig 6 PV output voltage

Fig 7 output power of boost converter

Fig 8 output power of boost converter
Fig 9 Gate voltage and voltage across switch

Fig 10 Current through $C_1$ and $C_2$

Fig.4.9 Current through $L_m$
V. CONCLUSION

Since the energy of the coupled inductor’s leakage inductor has been recycled, the voltage stress across the active switch \( S \) is constrained, which means low ON-state resistance \( R_{	ext{ON}} \) can be selected. Thus, improvements to the efficiency of the proposed converter have been achieved. The switching signal action is performed well by the floating step-up interleaved dc-dc converter with a common active clamp, for getting transformerless hybrid dc-dc converters, IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 55, no. 2, pp. 687–696, Mar. 2008.


