ZETA CONVERTER WITH COUPLED INDUCTOR FOR AC APPLICATIONS

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ABSTRACT

Dual-stage micro-inverters are generally used in grid-connected photovoltaic (PV) systems. The high step-up DC/DC converter is essential for the grid-connected micro-inverter because the input voltage from a single solar panel is very small. A DC/DC Zeta converter with coupled inductor which operates at moderate duty ratios is proposed. High voltage gain is achieved by employing high turns ratio to coupled inductor. The leakage-inductor energy of the coupled inductor is efficiently recycled to the load by additional capacitors and diodes and thus efficient energy-conversion is possible. The stress on the active switch is also restrained. Zeta converter with coupled inductor topology is simulated and voltage conversion ratio of 8 is obtained. AC output voltage is obtained by connecting it to an inverter. Voltage gain of 8 and an efficiency of 65% are achieved for the proposed system.

Keywords: Zeta Converter, Coupled Inductor

I. INTRODUCTION

Due to the decrease in world’s fossil fuel energy and its inability to meet the energy demand in the near future has lead to the use of renewable energy. As the world’s photovoltaic (PV) market is growing rapidly, the role of grid-connected PV systems in distribution energy systems will become important, and the PV inverter will also play an irreplaceable role in this increasing market. The ac module, which has been proposed to improve these problems, is called the micro-inverter. Solar micro-inverter is an inverter integrated to each solar panel module. The dual-stage micro-inverter combines a high step-up DC/DC converter and DC/AC inverter. By using this dual-stage micro-inverter, we can achieve efficiency as high as the conventional PV string-type inverter. The DC/DC converters used in the dual-stage micro-inverter of the grid-connected PV systems require high step-up voltage conversion.

II. CONVENTIONAL PWM ZETA CONVERTER

The pulse width modulation (PWM) Zeta converter is a step up/down converter of non-inverting polarity type and it can be designed to achieve low-ripple output current with separate inductors [1]. Zeta converter is used in power factor correction and voltage regulation designs.
lower than a custom transformer’s coefficient of greater than 0.99[3].

The leakage inductance of the coupled inductors can be employed to control the diode current falling rate and to alleviate the diode reverse-recovery problem[4]. A coupled inductor with a lower-voltage-rated switch is used for raising the voltage gain (whether the switch is turned on or turned off)[5]. Moreover, a passive regenerative snubber is utilized for absorbing the energy of stray inductance so that the switch duty cycle can be operated under a wide range, and the related voltage gain is higher than other coupled-inductor-based converters[5].

By replacing the input inductors of DC/DC converters with a cell formed by a coupled inductor and a diode leads to a family of converters with high voltage ratio[6]. The energy accumulated in the leakage inductance is transferred to the load through the diode. Thus the stress in the switch is also significantly reduced[7].

IV. ZETA CONVERTER WITH COUPLED INDUCTOR

The circuit configuration of the proposed DC to DC converter is shown in Fig 3. This topology is basically derived from a conventional Zeta converter by replacing the input inductor by a coupled inductor. The turns ratio of the coupled inductor increases the voltage gain[8] and the secondary winding of the coupled inductor is in series with a switched capacitor for further increasing the voltage[9]. In Fig 3 S1 is the floating active switch. The primary winding N1 of a coupled inductor is similar to the input inductor of the conventional boost converter, except that capacitor C1 and diode D1 recycles the leakage-inductor energy from N1. The secondary winding N2 is connected with another pair of capacitor C2 and diode D2 which recycles the leakage inductor energy from N2. Now N2, C2 and D2 all three are in series with N1. The diode D3 connects to the output capacitor C3 and load R.

III. COUPLED INDUCTOR

The coupled inductor consists of two separate inductors wound on the same core; they typically come in a package with the same length and width as that of a single inductor of the same inductance value, only slightly taller. The price of a coupled inductor is also typically much less than the price of two single inductors. The windings of the coupled inductor can be connected in series, in parallel, or as a transformer. Most of the coupled inductors have the same number of turns i.e., a 1:1 turns ratio but some newer ones have a higher turns ratio. The coupling coefficient, K, of coupled inductors is typically around 0.95, much

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2) The turns ratio $n$ of the coupled inductor winding is equal to $N_2/N_1$.
3) The ON-state resistance $R_{DS(ON)}$ and all parasitic capacitances of the main switch $S_1$ are neglected. The equivalent series resistance (ESR) of the capacitors $C_1$, $C_2$ and $C_3$ and the parasitic resistance of coupled-inductor are neglected.
4) The forward voltage drops of the diodes $D_1$, $D_2$ and $D_3$ are also neglected. The capacitors $C_1$, $C_2$ and $C_3$ are sufficiently large that the voltages across them are considered to be constant.

The various modes of operation for the proposed converter in continuous-conduction mode (CCM) are described as follows.

A. CCM Operation

Mode I $[t_0, t_1]$: In the transition interval $[t_0, t_1]$, switch $S_1$ and diode $D_2$ conducts. The current flow path is shown in Fig.4. The source voltage $V_{in}$ is applied on magnetizing inductor $L_m$ and primary leakage inductor $L_k$. Meanwhile, $L_m$ also releases its energy to the secondary winding, and also charges capacitor $C_2$ along with the decrease in energy. Thus the charging current $i_{o2}$ and $i_{c2}$ also decreases. The secondary leakage inductor current $i_{k2}$ is declines according to $i_{km}/n$. This mode ends when the increasing $i_{k1}$ equals the decreasing $i_{km}$ at $t = t_1$.

$$\begin{align*}
& i_{km} = i_{k1} - i_{k2} \\
& (\ldots) = (\ldots) - (\ldots)
\end{align*}$$

$$\begin{align*}
& (\ldots) = (\ldots) + (1 + 
\ldots) \\
& (\ldots) = (\ldots) + 
\ldots + 
\ldots
\end{align*}$$

Mode II $[t_1, t_2]$: In the interval $[t_1, t_2]$, switch $S_1$ remains ON and diode $D_3$ conducts. The source energy $V_{in}$ is series connected with $C_1$, $C_2$, secondary winding $N_2$, and $L_{k2}$ to charge output capacitor $C_3$ and load $R$. Meanwhile, magnetizing inductor $L_m$ is also receives energy from $V_{in}$. The current flow path is shown in Fig.5.

![Fig.5. Current flow path in Mode II](image)

Mode III $[t_2, t_3]$: In the interval $[t_2, t_3]$, switch $S_1$ is turned OFF and only diodes $D_3$ and $D_4$ conducts. The current flow path is shown in Fig.6. The secondary leakage inductor $L_{k2}$ keeps charging $C_3$ when switch $S_1$ is off. The energy stored in leakage inductor $L_{k1}$ flows through diode $D_1$ to charge capacitor $C_1$ instantly when $S_1$ turns off. The voltage across $S_1$ is the summation of $V_{in}$, $V_{km}$ and $V_{k1}$. Currents $i_{k1}$ and $i_{k2}$ are rapidly declining, but $i_{km}$ is increasing because $L_m$ is receiving energy from $L_{k2}$. Once current $i_{k2}$ drops to zero, this mode ends at $t = t_3$.

$$\begin{align*}
& (\ldots) = 0 \\
& (\ldots) = (\ldots) - (\ldots)
\end{align*}$$
Mode IV \([t_3, t_4]\): 
During the transition interval \([t_3, t_4]\), the energy stored in magnetizing inductor \(L_m\) releases simultaneously to \(C_1\) and \(C_2\). The current flow path is shown in Fig 7. Only diodes \(D_1\) and \(D_2\) are conducting. Currents \(i_{Lk1}\) and \(i_{Lk2}\) are persistently decreased because leakage energy still flows through diode \(D_1\) and continues charging capacitor \(C_1\). The \(L_m\) is delivering its energy through the coupled inductor and \(D_2\) to charge capacitor \(C_2\). The energy stored in capacitors \(C_3\) is constantly discharged to the load \(R\). The voltage across \(S_1\) is the summation of \(V_{in}\) and \(V_{Lm}\). This mode ends when switch \(S_1\) is turned on at the next switching period.

Mode V \([t_4, t_5]\): 
During the interval \([t_4, t_5]\), magnetizing inductor \(L_m\) is constantly transferring energy to \(C_2\). The current flow path is shown in Fig 8, and only diode \(D_2\) is conducting. The \(i_{Lm}\) is decreasing due to the magnetizing inductor energy flowing continuously through the coupled inductor to secondary winding \(N_2\) and \(D_2\) to charge capacitor \(C_2\). The energy stored in capacitors \(C_3\) is constantly discharged to the load \(R\). The voltage across \(S_1\) is the summation of \(V_{in}\) and \(V_{Lm}\). This mode ends when switch \(S_1\) is turned on at the next switching period.

The typical waveform of several major components during one switching period is shown in Fig. 9.
Fig. 9. Typical waveforms of the proposed converter at CCM operation

V. STEADY STATE ANALYSIS OF PROPOSED CONVERTER IN CCM

For the simplification of the steady-state analysis, only modes II and IV are considered for CCM operation, and the leakage inductances at primary and secondary sides are ignored.

From mode II:
\[ v_{Lm} = V_{in} \]
\[ v_{N2} = nV_{in} \]

From mode IV:
\[ v_{Lm} = -V_{c1} \]
\[ -V_{N2} = V_{c2} \]

By applying a volt-second balance on the magnetizing inductor \( L_m \) we get,
\[ \int (-) + \int = 0 \]
\[ \int + \int (-) = 0 \]

By solving the above two equations the voltages across C1 and C2 are obtained as
\[ (1 -) \]

The output voltage during mode II is,
\[ V_o = V_n + V_{c1} + V_{N2} + V_{c2} \]
\[ = (1 +) \]

The dc voltage gain \( M_{CCM} \) can be found as follows:
\[ = (1 +) \]

Voltage gain \( M_{CCM} \) as a function of duty ratio (D) by various turns ratio \( n \) is represented by a graph and the straightness of the curve accounts for the correction between turns ratio \( n \) and duty ratio (D) under the voltage gain \( M_{CCM} = 8 \).

VI. SIMULATION RESULTS

The proposed Zeta converter with coupled inductor turns ratio of \( n=3 \), which is basically derived from a conventional PWM Zeta converter, along with an inverter is simulated using MATLAB/Simulink software package. The voltage gain is obtained to be 8.

For an input voltage of 25V, at 50 KHz the Zeta converter output voltage is 205V. Thus a voltage gain of 8 is achieved. AC output voltage is obtained by connecting it to an inverter. The output waveforms are shown in Fig. 12 & Fig 13.
VII. CONCLUSIONS
This work explains a DC/DC Zeta converter with coupled inductor for dual-stage micro inverter.

REFERENCES