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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.

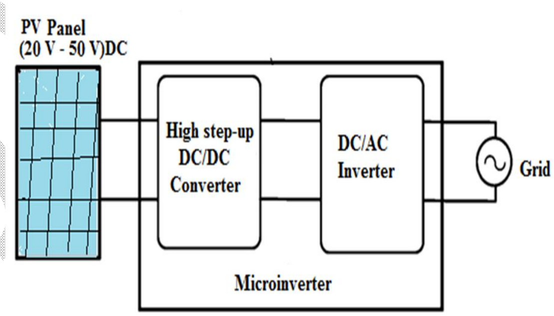

Fig.1. Dual-Stage Micro Inverter

The conventional Zeta converter is configured of two inductors, a series capacitor and a diode [2]. The most common operating modes of these PWM converters are the continuous inductor current mode (CICM or CCM) and discontinuous inductor current mode (DICM or DCM).

A. Continuous Conduction Mode

In CCM mode the switch has two sub-intervals in a switching period.
Considering,
D_1- the switch-on duty cycle
D_2- the diode-on duty cycle

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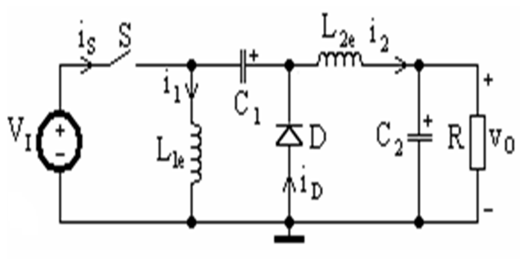

Fig. 2. Circuit diagram of PWM Zeta Converter

Assuming 100% efficiency, the duty cycle, D_1, for a Zeta converter operating in CCM is given by

$$D_1 = Vo/ (V_i + Vo)$$

where, V_i and Vo are the input and output voltages of PWM Zeta converter. This can be rewritten to obtain the output voltage of the converter in CCM mode,

$$= \frac{}{(1 - \quad)}$$

D_{1max} occurs at $V_{i(min)}$ and D_{1min} occurs at $V_{i(max)}$. The DC voltage conversion ratio of PWM Zeta converter with CCM is obtained as,

$$\frac{}{} = \frac{}{1 -} =$$

B .Discontinuous Conduction Mode

In DCM the switching period is divided into three sub-intervals. The third time interval of operation cycle is non-zero, not that either inductor current is discontinuous. The three distinct time intervals are namely $D_1 T_s$, $D_2 T_s$ and $D_3 T_s$ with $D_1 + D_2 + D_3 = 1$ for a constant switching frequency. D_3 is the switch and diode off ratio. The output voltage of the converter in DCM is

$$= \frac{}{}$$

The DC voltage conversion ratio is obtained as

$$= \frac{}{} = \frac{}{}$$

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 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 S_1 is the floating active switch. The primary winding N_1 of a coupled inductor is similar to the input inductor of the conventional boost converter, except that capacitor C_1 and diode D_1 recycles the leakage-inductor energy from N_1. The secondary winding N_2 is connected with another pair of capacitor C_2 and diode D_2 which recycles the leakage inductor energy from N_2. Now N_2, C_2 and D_2 all three are in series with N_1. The diode D_3 connects to the output capacitor C_3 and load R.

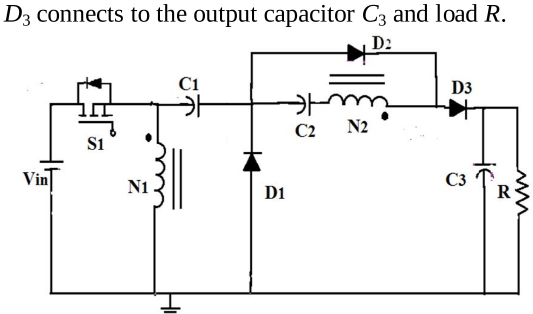

Fig. 3.Circuit diagram of the proposed system

Certain assumptions are made for the simplification of the circuit analysis.

1) All components are ideal, except for the leakage inductance of coupled inductor.

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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, C2 and C_3 and the parasitic resistance of coupled-inductor are neglected.
4) The forward voltage drops of the diodes D_1, D2 and D_3 are also neglected. The capacitors C_1, C2 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_{k1}; 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_{D2} and i_{C2} also decreases. The secondary leakage inductor current i_{Lk2} is declines according to i_{Lm} /n .This mode ends when the increasing i_{Lk1} equals the decreasing i_{Lm} at t = t_1.

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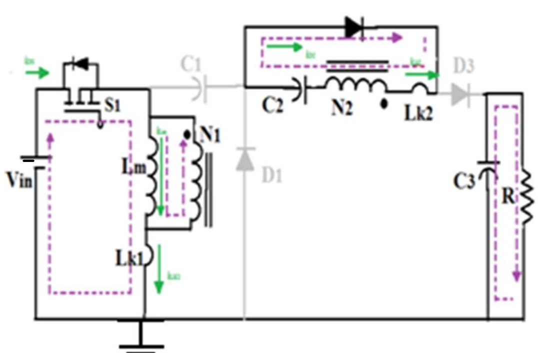

Fig.4. Current flow path in Mode I

***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.

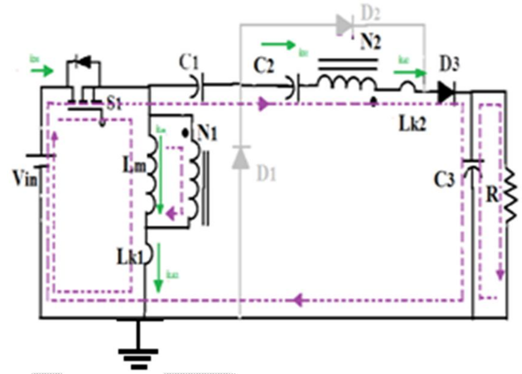

Fig.5. Current flow path in Mode II

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 from V_{in}; meanwhile, V_{in} is also in series with N_2 of coupled inductor and capacitors C_1 and C_2 are discharging their energy to capacitor C_3 and load R, which leads to increase in i_{Lm}, i_{Lk1}, i_{DS}, and i_{D3}. This mode ends when switch S_1 is turned off at t = t_2.

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***Mode III* [t_2, t_3]:**

In the interval [t_2, t_3], switch S_1 is turned OFF and only diodes D_1 and D_3 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_{Lm}, and V_{Lk1}. Currents i_{Lk1} and i_{Lk2} are rapidly declining, but i_{Lm} is increasing because L_m is receiving energy from L_{k2}. Once current i_{Lk2} drops to zero, this mode ends at t = t_3.

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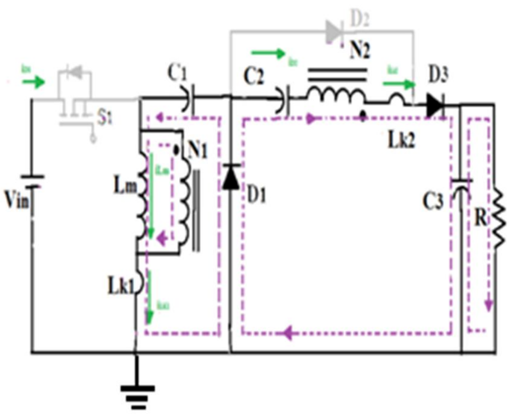

Fig. 6.Current flow path in Mode III

***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_{D1} are persistently decreased because leakage energy still flows through diode D_1 and continues charging capacitor C_1. The Lm 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. Currents i_{Lk1} and i_{Lm} are decreasing, but i_{D2} is increasing. This mode ends when current i_{Lk1} is zero at t = t_4.

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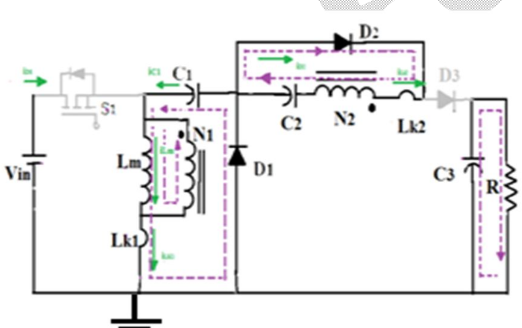

Fig. 7. Current flow path in Mode IV

***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 the next switching period.

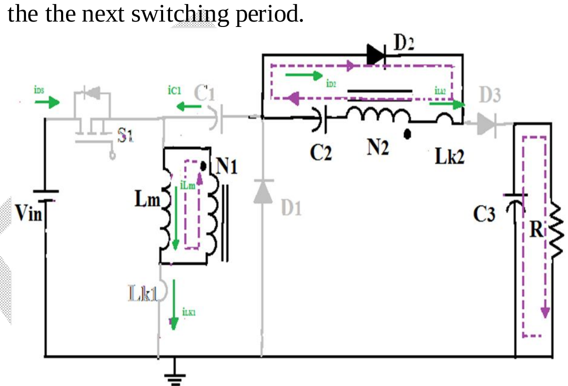

Fig. 8.Current flow path in Mode V

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The typical waveform of several major components during one switching period is shown in Fig. 9.

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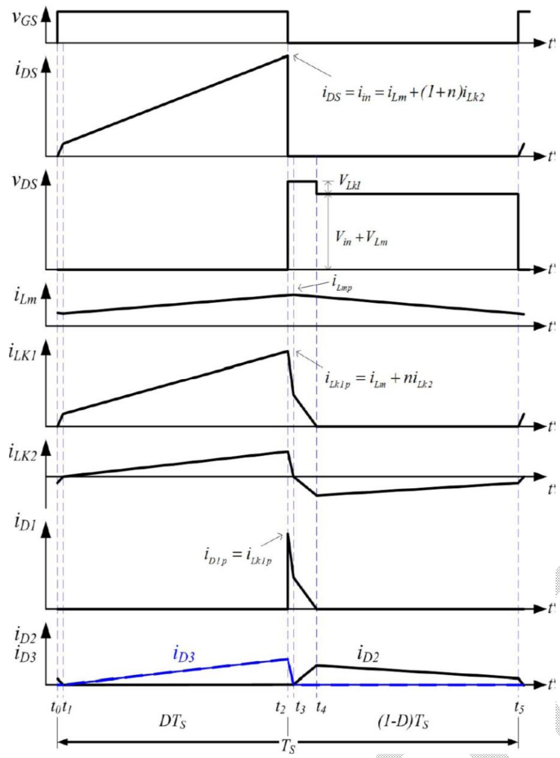

Fig. 9. Typical waveforms of the proposed converter at CCM operation

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 Lm we get, $\int \quad + \int (- \quad) = 0$

$$\int \quad + \int (- \quad) = 0$$

By solving the above two equations the voltages across C1 and C2 are obtained as

$$= \frac{}{(1 - \quad)}$$

$$= \frac{}{(1 - \quad)}$$

The output voltage during mode II is,

$$V_o = V_{in} + V_{c1} + V_{N2} + V_{c2}$$

$$= \frac{(1 + \quad)}{(1 - \quad)}$$

The dc voltage gain M_{CCM} can be found as follows:

$$= \frac{(1 + \quad)}{(1 - \quad)}$$

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.

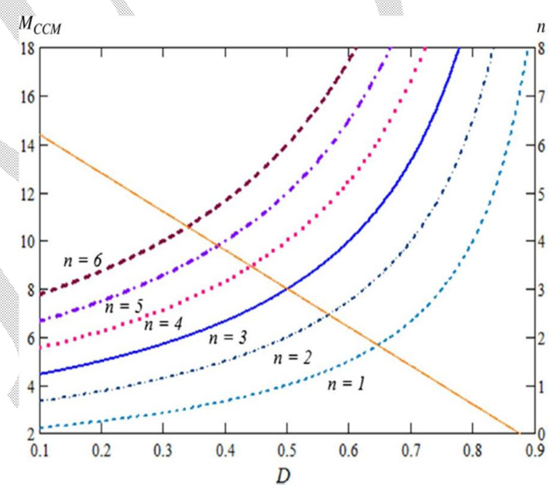

Fig. 10. M_{CCM} as a function of *D* by various turns ratios, and the turns ratio versus duty ratio under voltage conversion is 8

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.

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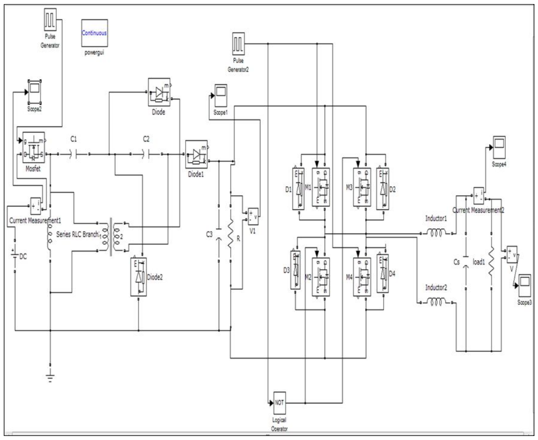

Fig. 11.Simulation Diagram of proposed Zeta converter with coupled inductor followed by an inverter

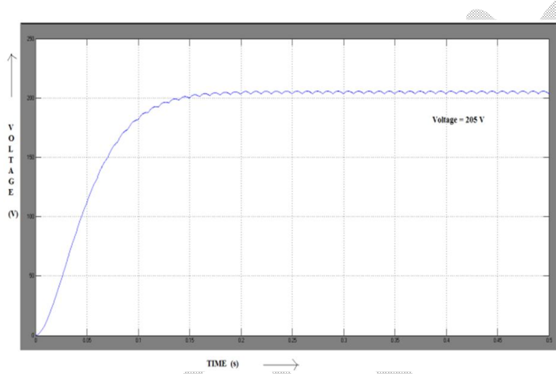

Fig.12. Output voltage waveform of Zeta converter

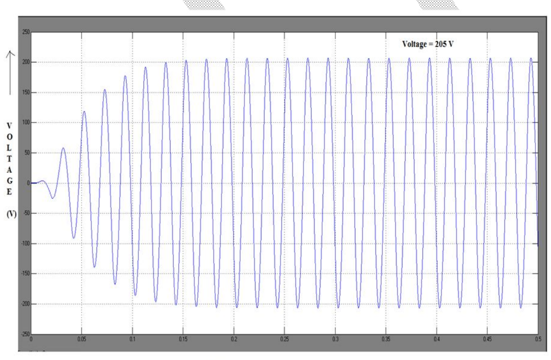

Fig.13.Output voltage waveform of the inverter

VII. CONCLUSIONS

This work explains a DC/DC Zeta converter with coupled inductor for dual-stage micro inverter. The turns ratio of the coupled inductor increases the voltage gain and the secondary winding of the coupled inductor is in series with a switched capacitor for further increasing the voltage. The energy of the leakage inductor of the coupled inductor is recycled to the load by using additional capacitors and diodes. Thus the voltage stress across the active switch is restrained and hence low ON- state resistance is obtained. The proposed system achieves a voltage gain of 8 and an efficiency of 65% is achieved.

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