ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 4, April 2014

Cascaded Boost Converter for PV Applications

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Abstract: Among renewable energy sources, solar power has the potential to become one of the main contributors to the future electricity supply. Low voltage photovoltaic systems require a high voltage gain converter for module's grid connection through a DC-AC inverter. This paper proposes a converter that achieves a high step-up voltage conversion ratio, which contains a coupled inductor, without extreme duty ratios and numerous turns-ratio; the leakage inductor energy of the coupled inductor is efficiently recycled to the load. Also, switch of the converter isolates energy from the PV panel when the ac module is off. This particular design protects installers and users from electrical hazards. These features explain module's high efficiency performance. A 15V input voltage, 200V output voltage, and 100W output power circuit of the proposed converter has been implemented. MATLAB is used for the study.

Keywords: AC module, coupled inductor, high step-up voltage gain, microinverter, maximum power point (MPP).

I. INTRODUCTION

India is poised at the threshold of opportunity to grow and expand its role in PV adoption and manufacturing and potentially to become a global leader in this technology. Specific drivers for PV in India include the country's rapidly rising primary energy and electricity needs, the persistent energy deficit situation, the country's overdependence on coal for electricity generation and on oil and gas imports. These factors coupled with India's endowment with abundant irradiation, with most parts of the country enjoying 300 sunny days a year, make PV particularly attractive to the country's energy strategy.

One of the major problems of PV systems is that the output voltage of PV panels is highly dependent on solar irradiance and ambient temperature. A conventional 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],[2]. Unfortunately, once there is a partial shadow on some panels, the system's energy yield becomes significantly reduced [3]. Hence, loads cannot be directly connected to the output of PV panels. A DC-DC converter is required to operate as an interface between PV panels and the inverter. The DC-DC boost converter fixes the output voltage of the PV system. It receives a variable input voltage, which is the output of PV panels, and yields a constant output voltage across its output capacitors where the loads can be connected.

PV systems, also termed solar microinverters, have gained greater visibility during the past several years as a convenient and promising renewable energy source. The main drawbacks of PV energy are the high cost of manufacturing silicon solar panels and the low conversion efficiency. With the newer techniques of manufacturing crystalline panels and efficient power converter design, it is possible to make a PV project cost-effective. The conversion of the output voltage from a solar panel into usable DC or AC voltage must be done at its Maximum Power Point, or MPP. MPP is the PV output voltage at which the PV module delivers maximum energy to load.

The microinverter includes a DC-DC boost converter and an inverter with a control circuit as shown in Fig 1. 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]. Using active clamp technique recycles the leakage inductor's energy but also constrains the voltage stress across the active switch. However the tradeoff 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

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ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
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with the voltage-multiplier or voltage-lift technique successfully accomplishes the goal of higher voltage gain [6]-[13].

In this paper the simulation and analysis of a highly efficient step-up converter for photovoltaic applications is performed. A PV panel with MPPT is given as the input. The output of converter is given to a micro inverter, which is finally connected to a grid which is loaded. A DC-DC converter acts as an interface between the load and the module Fig 1.

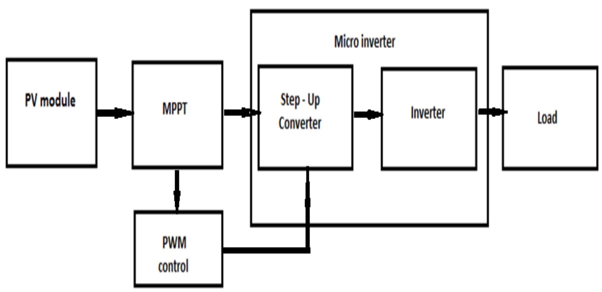

Fig 1: General block diagram

II. CIRCUIT CONFIGURATION AND OPERATION PRINCIPLE OF CONVERTER

The converter, shown in Fig 2, is comprised of a coupled inductor *T* with the floating active switch *S*. The primary winding N_1 of a coupled inductor *T* is similar to the input inductor of the conventional boost converter, and capacitor C_1 and diode D_1 receive leakage inductor energy from N_2. The secondary winding N_2 of coupled inductor *T* is connected with another pair of capacitors C_2 and diode D_2, which are in series with N_1 in order to further enlarge the boost voltage. The rectifier diode D_3 connects to its output capacitor C_3. This converter has several features: 1) The connection of the two pairs of inductors, capacitor, and diode gives a large step-up voltage-conversion ratio; 2) 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 3) the floating active switch efficiently isolates the PV panel energy during non operating conditions, which enhances safety [4].

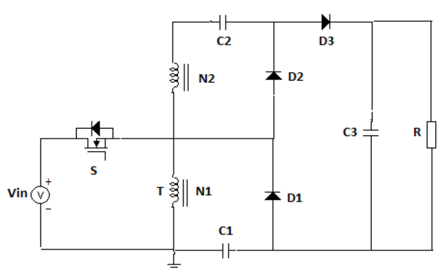

Fig 2: Circuit configuration of the converter

III. OPERATING PRINCIPLE AND STEADY-STATE ANALYSIS OF CONVERTER

A. CCM Operation

The converter is operated in CCM. There are five operating modes in a switching period [4].

Mode I: In this interval, the magnetizing inductor L_m continuously charges capacitor C_2 through T when S is turned on. The current flow path is shown in Fig switch S 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 to charge 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.

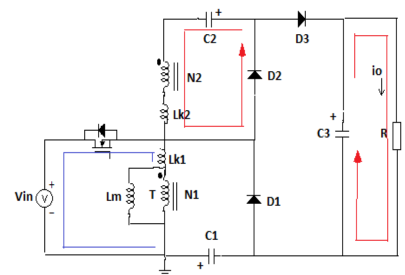

Fig 3: Current flow path of mode I

Mode II: During this interval, source energy V_{in} is series connected with N_2, C_1, and C_2 to charge C_3 and load R. At the same time magnetizing inductor L_m is also receiving energy from V_{in}. The current flow path is shown in Fig 4, where switch S remains on and only D_3 is conducting. The i_{Lm}, i_{Lk1} and i_{D3} are increasing because 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 serially

connected with N_2 of coupled inductor T, capacitors C_1 and C_2, and then discharges their energy to C_3 and R. The i_{in}, i_{D3} and discharging current $|i_{C1}|$ and $|i_{C2}|$ are increasing. This mode ends when switch S is turned off at $t = t_2$.

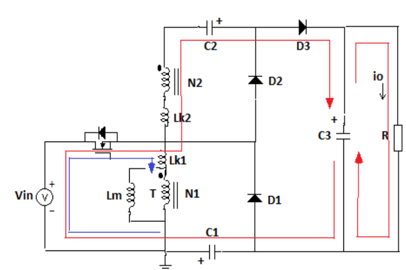

Fig 4: Current flow path of mode II

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 4, April 2014

Mode III: During this interval, secondary leakage inductor L_{k2} keeps charging C_3 when switch Sis off. The current flow path is shown in Fig 5, where only D_1 and D_3 are conducting. The energy stored in leakage inductor L_{k1} flows through D_1 to charge C_1 instantly when S is off. Meanwhile, the energy of secondary leakage inductor L_{k2} is series connected with C_2 to charge output C_3 and the load. Since leakage inductance L_{k1} and L_{k2} are far smaller than L_m, i_{Lk2} rapidly decreases. But i_{Lm} is increasing because L_m is receiving energy from L_{k1}. Current i_{Lk2} decreases until it reaches zero. This mode ends at $t = t_3$.

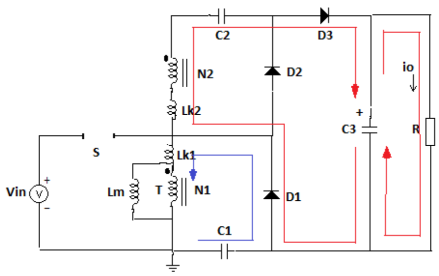

Fig 5: Current flow path of mode III

Mode IV: During this interval, the energy stored in magnetizing inductor L_m is released to C_1 and C_2 simultaneously. The current flow path is shown in Fig 6. Only D_1 and D_2 are conducting. I_{Lk1} and i_{D1} are continually decreased because the leakage energy flowing through D_1 keeps charging C_1. L_m is delivering its energy through T and D_2 to charge C_2. The energy stored in 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 $t = t_4$.

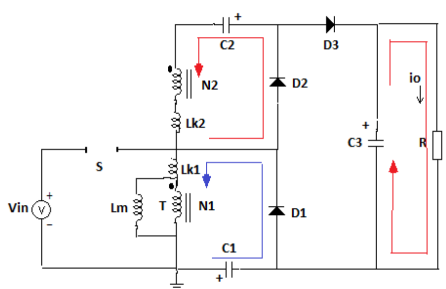

Fig 6: Current flow path of mode IV

Mode V: During this interval, only magnetizing inductor L_m is constantly releasing its energy to C_2. The current flow path is shown in Fig 7, in which only D_2 is conducting. The i_{Lm} is decreasing due to the magnetizing inductor energy flowing through the coupled inductor T to secondary winding N_2, and D_2 continues to charge C_2. The energy stored in C_3 is constantly discharged to the load R. This mode ends when switch Sis turned on at the beginning of the next switching period.

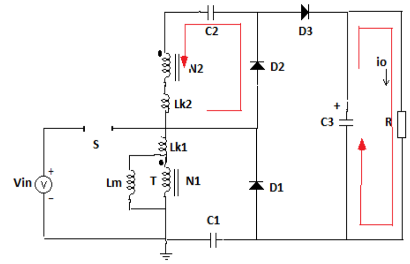

Fig 7: Current flow path of mode V

B. *Steady-State Analysis*

To simplify the steady-state analysis, only modes II and IV 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. [4]

$v_{Lm} = V_{in}$

$v_{N2} = nV_{in}$

During mode IV:

$v_{Lm} = -V_{C1}$

$v_{N2} = -V_{C2}$

Applying a volt-second balance on the magnetizing inductor L_m yields,

$$\int_0^{DTs}(V_{in})dt + \int_{DTs}^{Ts}(-V_{C1})dt = 0$$

$$\int_0^{DTs}(nV_n)dt + \int_{DTs}^{Ts}(-V_{C2})dt = 0$$

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 II,

$V_o = V_{in} + V_{N2} + V_{C2} + V_{C1}$ becomes,

$V_o = V_{in} + nV_{in} + nD/(1-D) V_{in} + D/(1-D) V_{in}$

The DC voltage gain MCCM can be found as follows:

$$M_{CCM} = V_o/V_{in} = (1+n)/(1-D)$$

During CCM operation, the voltage stresses on S and D_1-D_3 are given as:

$V_{DS} = V_{D1} = V_{in}/(1-D)$

$V_{D2} = nV_{in}/(1-D)$

$V_{D3} = (1+n)/(1-D)V_{in}$

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INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
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IV. DESIGN OF PV PANNEL & MPPT

The rapid increase in the demand for electricity and the recent change in the environmental conditions such as global warming led to a need for a new source of energy that is cheaper and sustainable with less carbon emissions. Solar energy has offered promising results in the quest of finding the solution to the problem. The harnessing of solar energy using PV modules comes with its own problems that arise from the change in insulation conditions. These changes in insulation conditions severely affect the efficiency and output power of the PV modules. A great deal of research has been done to improve the efficiency of the PV modules. A number of methods of how to track the maximum power point of a PV module have been proposed to solve the problem of efficiency.

The step-up converter is fed by a PV panel. A generalized photovoltaic model is implemented, which can be representative of PV cell, module or array, in order to estimate the electrical behaviour of the module with respect to change in environmental parameter i.e. insolation keeping the cell temperature constant. Due to the mismatch between load line and operating characteristic of the solar cells, the power available from the solar cells is not always fully extracted [5].

A MPPT is used for extracting maximum power from the solar PV module and transferring that power to the load. A DC-DC converter serves the purpose of transferring maximum power from the solar PV module to the load. By changing the duty cycle the load impedance as seen by the source is varied and matched at the point of the peak power with the source so as to transfer the maximum power. Therefore MPPT techniques are needed to maintain the PV array's operating at its MPPT.

Maximum power point tracking (MPPT) is a control technique to adjust the terminal voltage of PV panels so that maximum power can be extracted. MPPTs find and maintain operation at the maximum power point, using an MPPT algorithm. Many such algorithms have been proposed. However, one particular algorithm, the perturb-and-observe (P&O) method is used here because of its simplicity [30]-[33]. This is essentially a "trial and error" method. Fig 8 shows the P&O method flow chart. The PV controller increases the reference for the inverter output power by a small amount, and then detects the actual output power. If the output power is indeed increased, it will increase again until the output power starts to decrease, at which the controller decreases the reference to avoid collapse of the PV output due to the highly non-linear PV characteristic. Perturb and observe method is dominantly used in practical PV systems for the MPPT control due to its simple implementation, high reliability, and tracking efficiency [32].

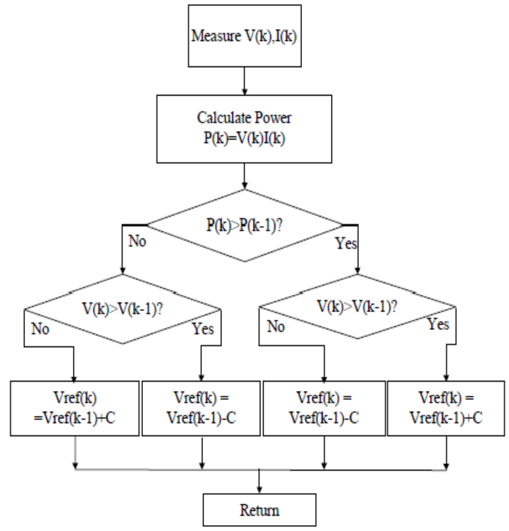

Fig 8: P&O method flow chart [32]

V. CONTROL STRATEGY

Pulse-width modulation (PWM) technique is used here. The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast pace. The longer the switch is on compared to the off periods, the higher the power supplied to the load is. PWM is one of the two principal algorithms used in photovoltaic solar battery chargers, the other being MPPT. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero.

VI. SIMULATION RESULTS AND ANALYSIS

The simulation of the converter is done in Matlab/Simulink. The designed converter consists of single active switch, which acts as high state drive. It also contains the coupled inductor, 2 diodes and 2 capacitors used to step-up the voltage level and it also recycles the leakage energy. One diode is used as rectifier diode.

A. Parameter Selection

The parameters used for the simulation are input voltage 15V, output voltage 200V. S is a MOSFET. Since (10) assign turns ratio n = 5, the duty ratio D is derived as 55%.

Switching frequency = 50 kHz
Full-load resistance R = 400 Ω
$C_1 = C_2$ = 47 μF
C_3 = 220 μF.

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INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 4, April 2014

B. Simulation Results

MATLAB/Simulink model of the converter with PV panel & MPPT is shown in the Fig 8 and MPPT by P & O method is shown in Fig 9. The switch used for the simulation is MOSFET, for recycling and rectifying diodes are used. The output voltage is obtained to be 200V for step-up operating mode where the input voltage is 15V.

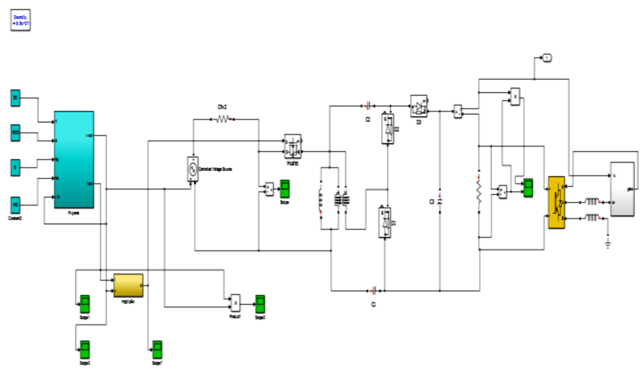

Fig 9: MATLAB/Simulink model of the converter with PV panel & MPPT

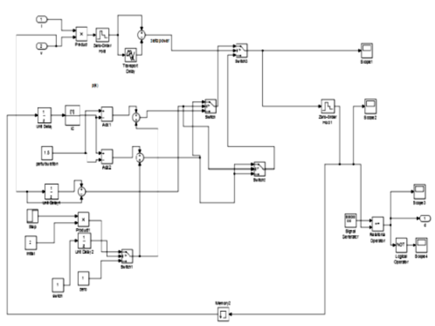

Fig 10: MATLAB/Simulink model of MPPT by P & O method

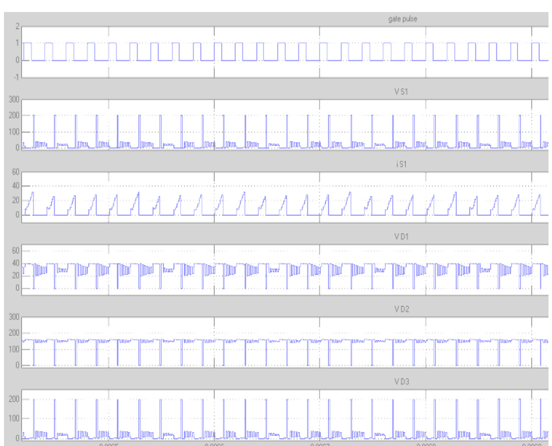

Fig 11: Waveforms at 15V input voltage with full-load condition and output 100W

The waveforms of the converter with 15V input voltage at full load are shown in Fig 11. Pulses are generated using MPPT. Output voltage and power waveforms are shown in Fig 12.

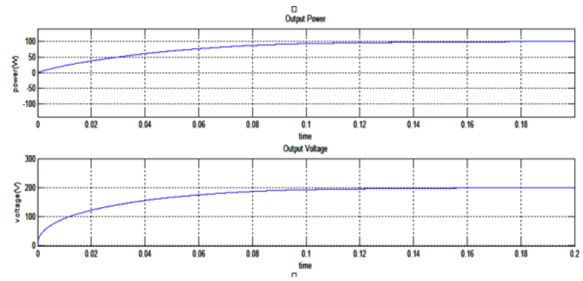

Fig 12: Waveform of output voltage and power

VII. CONCLUSION

In this paper a PV system has been simulated by Matlab/Simulink. Perturb and Observe algorithm has been used for maximum power point tracking. Simulation results show that the system operates in the maximum power point for the different irradiances values. In the converter the energy of leakage inductors has been effectively recycled and voltage stress across the switch is constrained. The switch here acts as a high state drive and also it protects panel and installers from the electrical hazardous while the switch is in the off state. The switching action is performed well by the switch during the system operation at all the condition, with eliminating the residential energy effectively during non operating condition. Without an extreme duty ratio and with a numerous turns ratio, the proposed converter achieved high voltage step-up gain. Thus improvement to the efficiency of the PV pannel has achieved.

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ISSN (Online) 2321 – 2004
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