Voltage Multiplier Module for Renewable Energy System with High Step-Up and High Efficiency Converter

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***Abstract*— A high step-up dc-dc converter which is suitable for renewable energy system is proposed in this paper. The topology used in the proposed converter is voltage multiplier module. The voltage multiplier module consists of switched capacitors and coupled inductors which makes the high step-up high-efficiency dc-dc converter in to interleaved boost converter. The input of the proposed converter can be renewable energy source (photovoltaic system or fuel cell or wind turbine etc) any one of the renewable energy system but this paper consists of only photovoltaic system. This proposed converter produces high step-up gain with low input current ripple, low conduction losses, low cost and high efficiency. Finally the basic circuit with input voltage 40V, 380V output, and 1000W output power is operated to justify its performance.**

Keywords- Photovoltaic System, High Step-Up Converter, Boost-Flyback Converter, Voltage Multiplier Module

I. INTRODUCTION

Renewable energy is produced from nature which will be restored constantly. It is produced from various sources in order to produce electricity such as solar energy, sun, wind, ocean, hydropower, geothermal sources, biomass, bio fuels and hydrogen. Because the renewable energy is cheaper and efficient, their share of total energy consumption is increasing. They produce power, heat or mechanical energy by converting those to electricity or to motive power. As it consists of low input voltage the high step-up dc-dc converters are employed in order to step-up the voltage and this resultant voltage is converted to ac by using an inverter[1]-[4].fig1 shows a renewable energy system which consists of step-up dc-dc converter and an inverter used for ac applications .

The high step-up converter is an important stage in the above fig typical renewable energy system because such a system requires a sufficient high step-up conversion with high–efficiency. There are many methodologies used in high step-up converters to achieve high step-up conversion with high efficiency as follows. The high step-up converter requires two stage converters with cascade structure for sufficient step-up gain, but this increases the cost and decreases the efficiency. In basic step-up dc-dc converters the boost and flyback converter consists of high resistances of the elements and leakage inductance this cause's high voltage stresses resulting no achievement of high step-up gain and high efficiency [5]-[8].

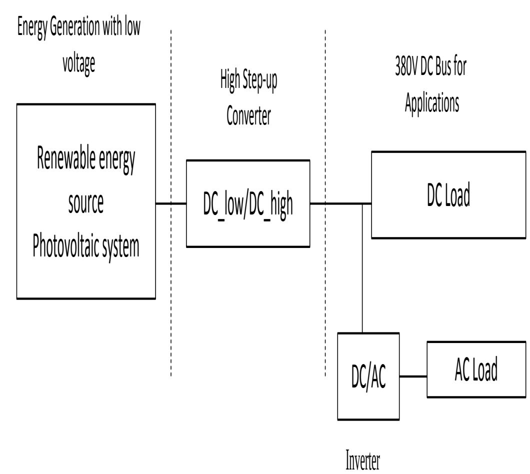

Fig. 1Typical renewable energy system

To operate the high step-up single switch converters at heavy load produces large current ripple and that increases the conduction losses. The conventional interleaved boost converter will be the perfect suitable approach. So, there have to modify the interleaved boost converter according to the mentioned conditions for high power application. To merge switched capacitors in conventional Interleaved boost converter will provide double voltage but no implementation of coupled inductors cause the limited step-up voltage [9]-[11]. Oppositely to merge only coupled inductors in conventional interleaved boost converter provide higher voltage but no implementation of switched capacitors may cause the step-up voltage to be normal. Hence, therefore there have to mitigate and implement the switched capacitors and coupled inductors to produce high step-up voltage, high efficiency and low voltage stresses for high applications.

The conventional interleaved boost converter called the proposed converter is merged with voltage multiplier module. This voltage multiplier module consists of coupled inductors to increase the step-up voltage, and the switched capacitors for extra voltage conversion ratio [12]-[15].

In the middle of the operation when any one of the switches turns off the energy stored in magnetizing inductor will transfer it to three respective paths, so, the current distribution will make current across diode zero before the diode is turnoff , this results in decreasing the diode reverse recovery losses[16]-[18].

Merits of the proposed converter are as follows:

1. The proposed converter produces low current ripple and low conduction losses that increases the lifetime of renewable energy sources which makes it suitable for high-power applications.
2. As the renewable systems require high step-up gain that can be achieved by the proposed converter.
3. The large voltage spikes are avoided and the efficiency is improved by recycling the energy to the output terminal due to the lossless passive clamp performance.
4. Because of implementing low voltage rated power switch with low RDS (ON), the voltage stresses on main switches and diodes are lower than output voltage, produces low cost and high efficiency.
5. Due to the internal configuration of the proposed converter makes some diodes decrease conduction losses and reduce the recovery losses of reverse diode.

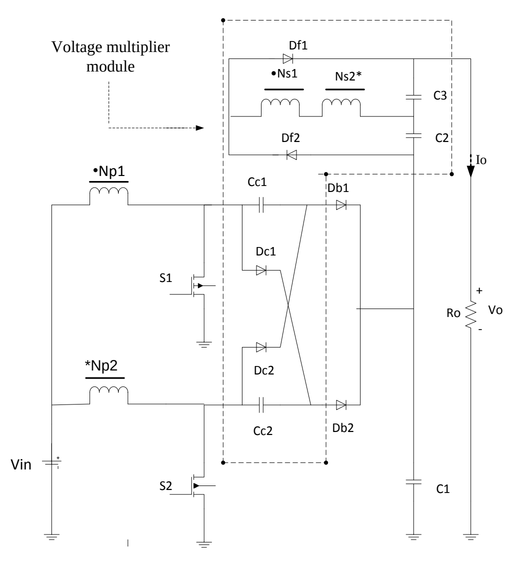

Fig.2 Boost converter

II. OPERATING PRINCIPLES

The high step-up interleaved converter with a voltage multiplier module is shown in fig2. The voltage multiplier module consists of two switches capacitors and two coupled inductors which are inserted in between the basic interleaved converter in order to form a modified boost-flyback-forward interleaved structure.

In the proposed converter work as a forward converter and flyback converter when switch is under on state and off state.

The primary windings are termed with turns and the secondary windings are termed with and N_s turns .The equivalent circuit of the proposed converter is shown in fig3, the denoted symbols are as follows.

L_{m1} and L_{m2} denote the magnetized inductors, L_s denote series leakage inductor, $L_{k1} and$ L_{k2} denote the leakage inductors, $D_{f1} and$ D_{f2} denote flyback-forward output diodes, $D_{b1} and$ D_{b2} denote boost operation output diodes, $D_{c1} and$ D_{c2} denote the clamp diodes, $C_{c1} and$ C_{c2} denote clamped capacitors , C_1, C_2, C_3 denote output capacitors and $S_1 and$ S_2 represents the power switches.

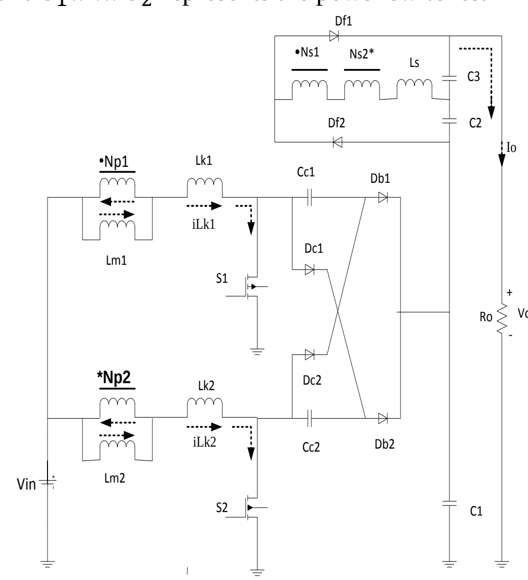

Fig.3 Equivalent circuit of the preferred converter

In the operation the proposed converter operates in continuous conduction mode, and during steady state the duty cycle of the power switch is greater than 0.5 and are integrated with 180° phase shift.

For suppression of input current ripple the proposed converter is operated in continuous conduction mode (CCM) is more suitable than the proposed converter is operated in discontinuous conduction mode (DCM) because the peak current in DCM is larger.

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Mode-1:

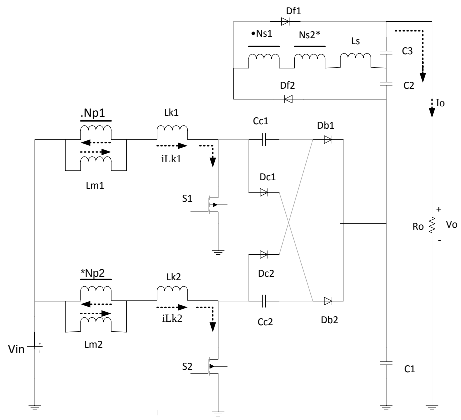

Fig.4 Mode-1

In this mode the power switches S_1 is in ON state and S_2 is in ON state, and the clamp diodes D_{c1}, D_{c2}, the output diodes used for boost operation D_{b1}, D_{b2}, the output diode used for flyback operation D_{f1} are reverse biased. L_s releases the stored energy to the output terminal or the D_{f2}, then the current through series leakage inductor L_s decreases to zero. So, the magnetizing inductor L_{m1} transfers energy to secondary side of coupled inductors. The current through leakage inductor L_{k1} increases linearly, and the other current through leakage inductor L_{k2} decreases linearly.

Mode-2:

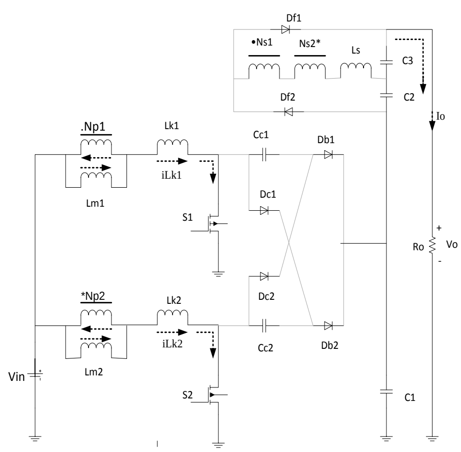

Fig.5 Mode-2

In this mode of operation both the power switches S_1 and S_2 are in ON state .the currents through both the leakage inductors L_{k1} and L_{k2} are increased linearly due to the reason charging input voltage source V_{in}

Mode-3:

In this mode of operation the power switch S_1 in ON state and the power switch S_2 is in OFF state. The clamped diode D_{c1} , the output diode for boost operation D_{b1}, the output diode used for flyback operation D_{f2} is reverse biased.

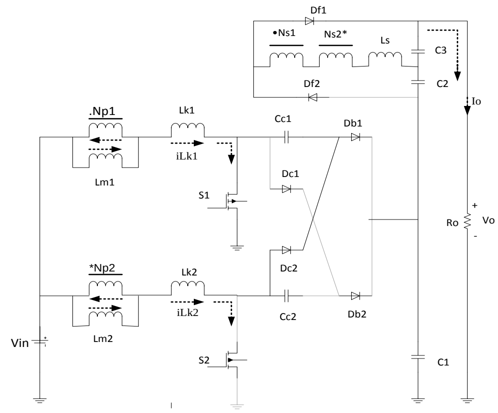

Fig.6. Mode-3

The energy which was stored in magnetizing inductor L_{m2} transfers to the secondary side of the coupled inductors, and the current through series leakage inductor L_s flows to capacitor C_1 or the flyback forward diodeD_{f1}. The voltage stress on power switch S_2 is clamped by clamp capacitor C_{c1} then this voltage is equal to the output voltage of the boost converter. Then theV_{in}, L_{m2}, L_{k2}, and clamp capacitor C_{c2} release energy to the output terminal therefore, V_{c1} obtains a double output voltage of the boost converter.

Mode-4:

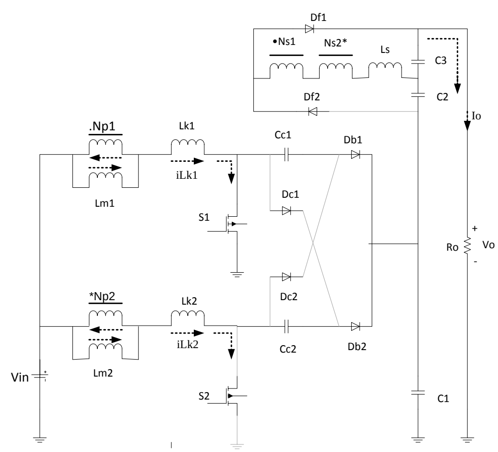

Fig.7. Mode-4

In this mode of operation the current iD_{c2} has naturally decreased to zero due to the magnetizing current distribution, and hence, diode reverse recovery losses are alleviated and conduction losses are decreased. Both power switches and all diodes remain in previous states except the clamp diode D_{c2}.

Mode-5:

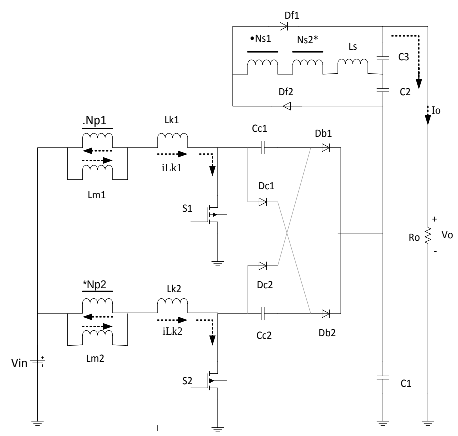

Fig.8 Mode-5

In this mode of operation the diodes Dc1, Dc2, Db1, Db2, and Df2 are reversed biased and the switch S1 remains in ON state, and the switch S2 is ready to turn on.. The series leakage inductors Ls allow to leave the stored energy to the output terminal via flyback–forward diode Df1, and the current through series leakage inductors decreases to zero. So, the magnetizing inductor Lm2 still transfers energy to the secondary side of coupled inductors. The current through leakage inductor Lk2 and Lk1increases and decreases dimensionally.

Mode-6:

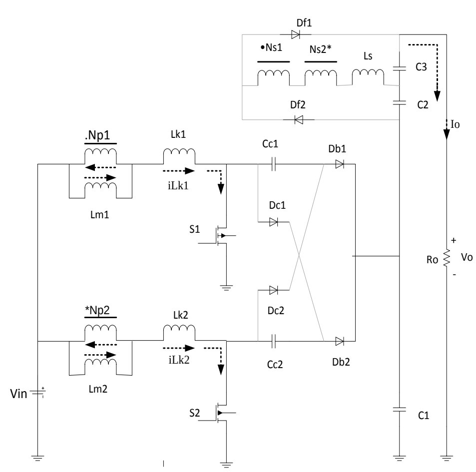

Fig.9. Mode-6

In this mode of operation, and all the diodes are remained in reversed biased and both of the power switches S1 and S2 remain in ON state.The currents are linearly increased between the leakge inductors Lk1 and Lk2 due to the charge input voltage source Vin.

Mode-7:

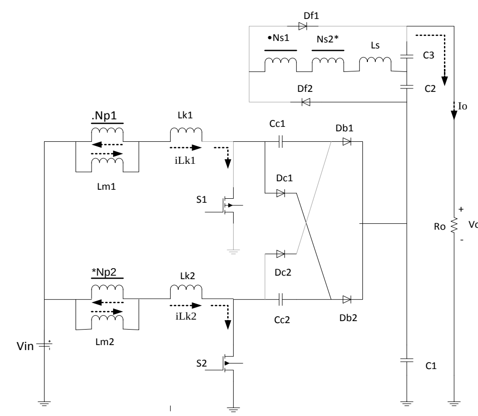

Fig.7. Mode-7

In this mode of operation, the power switch S2 is in ON state, and the other power switch S1 ready to turn off. The diodes Dc2, Db2, and Df1 are reversed biased. The energy stored in magnetizing inductor Lm1 carry to the secondary side of coupled inductors, and the current through series leakage inductors flows to output capacitor C2 via flyback–forward diode Df2. The power switch S1which consists of voltage stress is clamped by clamp capacitor Cc2 that increases output voltage of the boost converter. The input voltage source, magnetizing inductor Lm1, leakage inductor Lk1, and clamp capacitor Cc1 transfers energy to the output terminal; thus, VC1produces twice the output voltage of the boost converter.

Mode-8:

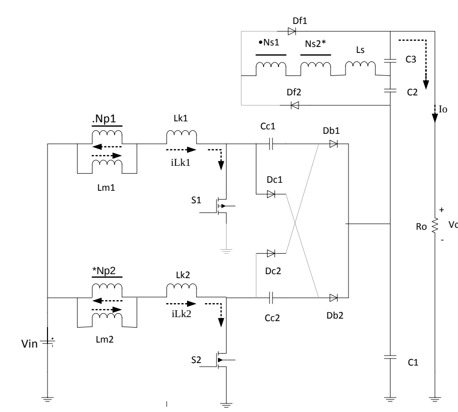

Fig.8. Mode-8

In this mode of operation, the current iDc1shrinks to zero due to the magnetizing current distribution, and hence, diode reverse recovery losses are alleviated and conduction losses are decreased. Both power switches and all diodes remain in previous states /except the clamp diode Dc1.

III. STEADY STATE ANALYSIS

In this steady state analysis the transient characteristics of circuitry is avoided to simplify the circuit performance analysis of the proposed converter in continuous conduction mode, and there are some assumptions are as follows:

- The components in the preferred converter are said to be ideal.
- The leakage inductors in the proposed converter L_{k1}, L_{k2} *and* L_s are neglected.
- Because of infinitely large capacitance the voltages of all capacitances are considered to be constant.
- Due to the complete interleaved structure the related components are defined in corresponding symbols such as D_{c1} *and* D_{c2} are defined as D_c

A. Step–Up Gain

$$V_{cc} = \frac{1}{1-D} V_{in} \qquad (1)$$

Where,

V_{cc}, the voltage of clamp capacitor is regarded as the output voltage of boost converter. In the system when any power switch is turn off then V_{c1} can obtain a double output voltage of the boost converter then,

$$V_{c1} = \frac{1}{1-D} V_{in} + V_{cc}$$

$$V_{cc} = \frac{1}{1-D} V_{in}$$

$$V_{c1} = \frac{2}{1-D} V_{in} \qquad (2)$$

From the energy transformation of primary side the output filter capacitors $C_{2\,and}\, C_3$ are charged. V_{c2} is equal to induced voltage of N_{s1} plus the induced voltage of N_{s2} when S_1 is in ON state , S_2 is in OFF state and S_2 is in ON state, S_1 is in OFF state. Therefore the voltages V_{c2} and V_{c3} are derived from

$$V_{c2} = V_{c3} = \frac{n}{1-D} V_{in} \qquad (3)$$

The output voltage can be derived from,

$$V_o = V_{c1} + V_{c2} + V_{c3}$$

$$V_o = \frac{2n+2}{1-D} V_{in} \qquad (4)$$

$$\frac{V_o}{V_{in}} = \frac{2n+2}{1-D}$$

B. Voltage Stress On Semiconductor Component

The voltage ripples of the capacitors are ignored to simplify the voltage stress analysis of the components used in the proposed converter. The voltage stress on power switch S_1 and S_2 are derived from

$$V_{s1} = V_{s2} = \frac{2}{1-D} V_{in}$$

$$V_{s1} = V_{s2} = \frac{1}{n+1} V_o \qquad (5)$$

The voltage stress on diode D_c is derived from

$$D_c = V_{c1}$$

$$V_{Dc1} = V_{Dc2} = \frac{2}{1-D} V_{in} = \frac{1}{n+1} V_o \qquad (6)$$

The voltage stress on diode D_b is derived from

$$V_{Db1} = V_{Db2} = V_{c1} - V_{cc}$$

$$V_{Db1} = V_{Db2} = \frac{1}{2n+2} V_o \qquad (7)$$

The voltage stress on diode D_f is derived from

$$V_{Df1} = V_{Df2} = \frac{2n}{1-D} V_{in} = \frac{n}{n+1} V_o \qquad (8)$$

C. Analysis Of Conduction Losses

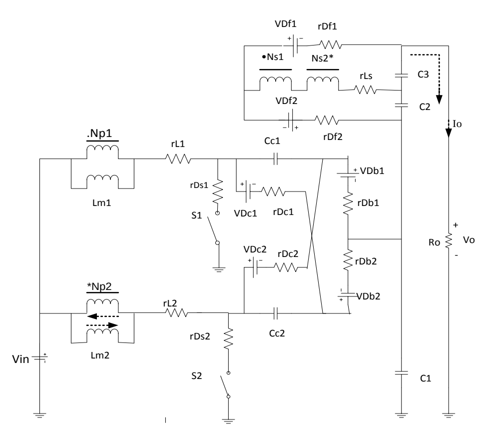

Fig.9 equivalent circuit of proposed converter including conduction losses

Usually the conduction losses are caused by resistances of semiconductor components and coupled inductors. In the proposed converter except the capacitors, all the components are assumed to be ideal. Because of energy recycling the characteristics of leakage inductors are ignored. The equivalent circuit consists of conduction losses of coupled inductors and semiconductor components where,

r_{L1} *and* r_{L2}= copper resistances of the primary windings of the coupled inductor

r_{Ls}= copper resistances of the secondary windings of the coupled inductors

r_{Ds1} *and* r_{Ds2}= on resistances of power switches

$V_{Dc1}, V_{Dc2}, V_{Db1}, V_{Db2}, V_{Df1}, V_{Df2}$= forward biases of the diodes

$r_{Dc1}, r_{Dc2}, r_{Db1}, r_{Db2}, r_{Df1}, r_{Df2}$= resistances of the diodes

Finally the voltage second balance and capacitor charge balance, the voltage conversion ratio with conduction losses can be derived from,

$$\frac{V_O}{V_{in}} = \frac{\frac{2n+2}{1-D} - \frac{1}{V_{in}}.(V_{Dc}+V_{Db}+2V_{Df})}{1+\frac{(2d-1).r_w+r_x}{R_O.(1-D)}+\frac{[(2D-1).r_y]+r_z}{R_O.(1-D)}} \qquad (9)$$

Where,

$$r_w = [2(2-D)(n+1)-1.5]r_{DS} + 4n(1-D)r_{Dc}$$

$$r_x = 2n(2n+1)r_{DS} + (2n+2)(2nD+2D-1)r_L$$

$$r_y = 2(1-2n)r_{Dc} + 0.5r_{Db}$$

$$r_w = 4n^2 r_L + 2(r_{Ls}+r_{Df})$$

Because the turn ratio n and copper resistances of the secondary windings of the coupled inductors are directly proportional, the copper resistances of the coupled inductors can be expressed as $r_{Ls} = 2n \cdot r_L$

Efficiency is expressed as follows:

$$\eta = \frac{1 - \frac{1-D}{V_{in}(2n+2)}.(V_{Dc}+V_{Db}+2V_{Df})}{1+\frac{(2D-1).r_w+r_x}{R_O.(1-D)^2}+\frac{[(2D-1).r_y]+r_z}{R_O.(1-D)}} \qquad (10)$$

from this we can say that the efficiency will be higher value if the input voltage is higher than the summation of the forward biases of all the diodes or if the resistance of the load is larger than the resistances of coupled inductors and semiconductor components.

In addition, the highest effect for efficiency is duty cycle, and the secondary is the copper resistance of coupled inductors.

D. Performance Of Current Distribution

When any switch is turned off the energy which is stored in the magnetizing inductors transfer it to three paths respectively. Therefore, the distribution decreases the conduction losses and increases the capacity by lower peak value of current. When the load is not heavy then the current through some diodes decrease to zero before the switch is turned off, which reduces the diode recovery losses.

E. Considerable Applications Of The Proposed System

All renewable energy sources are low voltage sources and there need high step-up conversion to supply power to a high voltage applications.

The proposed converter suppresses the input current ripple by lengthening the life time of the renewable energy sources.

IV SIMULATIONS AND RESULTS

(A) Simulation Diagram

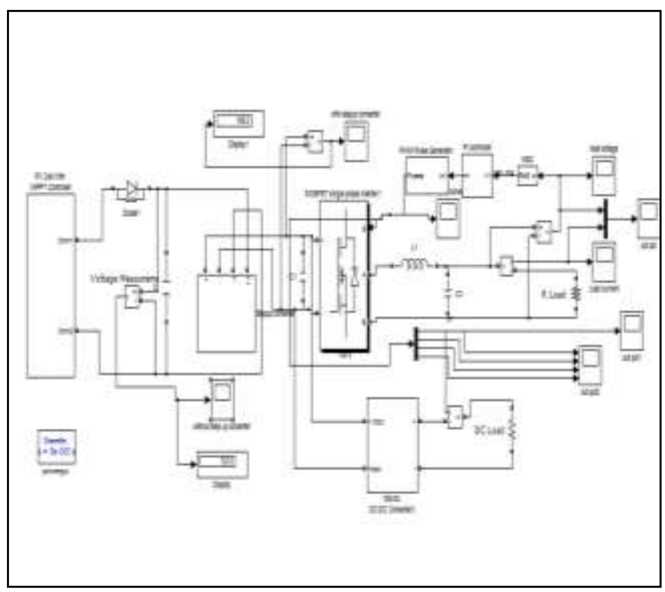

Fig.10 simulink diagram

The proposed converter receives the input voltage from renewable energy source such as fuel cell or photovoltaic cell etc. Here in this paper the renewable energy source photovoltaic cell is used. Photovoltaic cell is also known to be solar cell. Solar cell converts sun light in to electricity. A successive series collection of photovoltaic cells are connected in order to get solar panel which provides higher applicable voltage. Maximum power point controller is used in order to reach maximum power for the photovoltaic cell. This output voltage from the photovoltaic cell the renewable energy source is given to the input of the proposed converter.

(B) Output Waveforms

1. Output voltage without using step-up converter

The input photovoltaic voltage is controlled by using maximum power point controller to reach the maximum power thus, it results the output voltage V=133.3V. This is the particular voltage before using the step-up converter

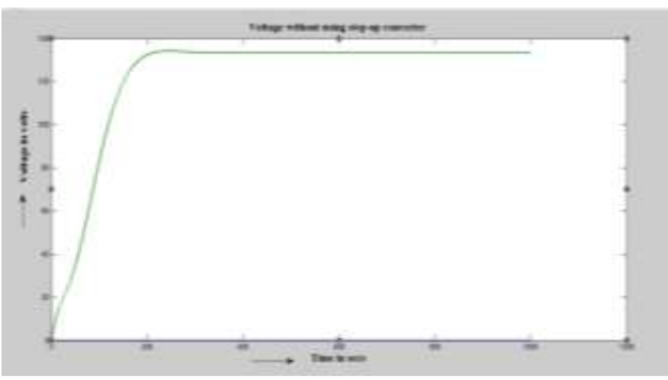

Fig.11 waveform of output voltage before using step-up converter

2. Output voltage using step-up converter

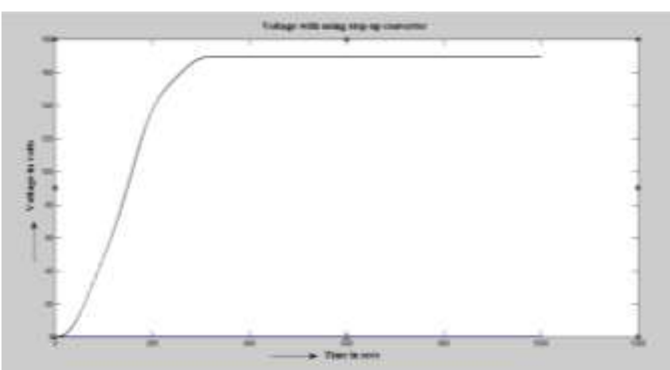

Fig.12 waveform of output voltage after using step-up converter

The output voltage from the photovoltaic cell is taken and is given to the proposed converter to step-up the voltage. By using the voltage multiplier module in this proposed converter it results to extend the step-up gain. V=169.2V.

3. Ac Load Voltage

The step-up voltage is given to inverter in order to convert dc voltage in to ac voltage. The following inverter outputs of voltage, current and power is shown in fig 13, fig 14, and fig 15.

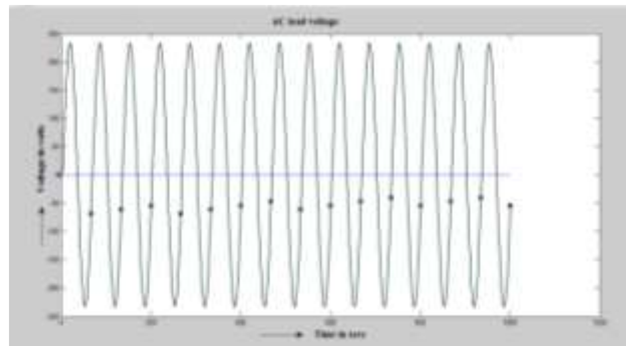

Fig.13. output waveform of AC load voltage

4. Ac Output Load Current

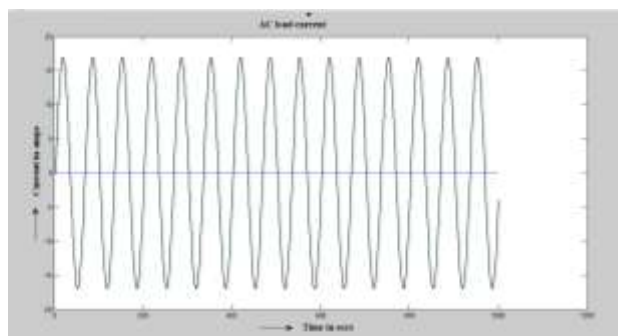

Fig.14.output waveform of AC load current

As the output load current is deduced from the inverter it is in sinusoidal which is of the similar magnitude of ac output voltage after merging the voltage multiplier module the load current is also increased.

5. AC Load Output Power

As the voltage in the system is increased twice using the voltage multiplier module in the preferred converter, substantially the current increases thus, the power value is alo increased as it is proportional to the product of voltage and current. Output power $P_o = 230W$

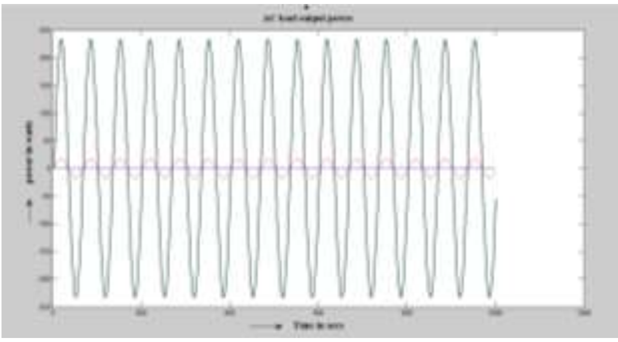

Fig.15. output waveform of AC power

6. Efficiency

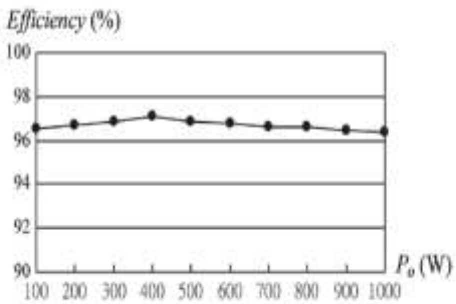

Fig.16 Efficiency of the converter

This proposed converter not only extends the step-up gain but also increases the efficiency by using a low voltage rated power switch with lowR_{DS}. Fig16 shows the measured efficiency of the proposed converter. At full load the efficiency is 96.4% at P_o=1000W. The maximum efficiency is 97.1% at P_o=400W.

V.CONCLUSION

The proposed converter has favourably implemented an coherent high step-up conversion through the voltage multiplier module. The interleaved structure reduces the input current ripple so, the voltage spikes are reduced by recycling the leakage energy. The power switch consists of voltage stress which is lower than the output voltage. The full load efficiency is 96.4% at $P_o = 1000W$ and the maximum efficiency is 97.1% at $P_o = 400W$.The converter is applicable for high power or renewable energy applications that need high step-up conversion.

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